

ICHNOFOSSILS OF THE CARBONATE PLATTEVILLE FORMATION
(MIDDLE ORDOVICIAN)
IN SOUTHEASTERN MINNESOTA

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ABSTRACT

The carbonates of the Platteville Formation (Tippecanoe sequence) were deposited in the epeiric sea which occupied the Hollandale Embayment during the middle Ordovician. The ichnofossils found within the Platteville are numerous, diverse, and moderately well preserved. The entire assemblage conforms generally with the Cruziana ichnofacies. A total of 20 ichnogenera have been recognized: Arenicolites, Bifungites, Chondrites, Conostichus, Cylindrichnus, Diplichnites, Fustiglyphus, Gyrolithes, Lingulichnus, Muensteria, Nereites, Palaeophycus, Planolites, Rhizocorallium, Rusophycus, Subphyllochorda, Teichichnus, Thalassinoides, (?)Torrowangea and Trypanites. Two additional genera, Diplocraterion and Skolithos are found in the subjacent St. Peter and Glenwood Formations. The most characteristic biogenic feature of the Formation is the high degree of bioturbation, which effectively destroyed earlier burrows.

The isochronous Deicke (Carimona) bentonite horizon is typified by seven traces: Arenicolites, Bifungites, Chondrites, Lingulichnus, Planolites, Thalassinoides, and Problematica type I. This association indicates shallow marine deposition estimated to be 10 to 20 meters in depth, under essentially uniform environmental conditions.

The Deicke bentonite is estimated to have been compressed from an original minimal thickness of 27 cm to the present 7.0 cm average thickness based on the compression of Chondrites and Planolites burrows within the ash

layer. Shale interbeds are estimated to have been 3 to 5 times their present thickness based on compressed Chondrites burrows.

The periodic influx of terrigenous sediments may have had an adverse effect upon some members of the benthic community, resulting in nonbioturbated laminated shale horizons. The presence of Chondrites among laminated shales and some lime-mudstones, and the absence of any other traces, may indicate that interstitial waters had a low oxygen content.

Orientation of orthoconic cephalopods within the Platteville shows a strong northwest-southeast trend. It is suggested that these animals were oriented after death with the long axes of the shells parallel to a southeast current flow from the Transcontinental Arch across the embayment.

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I would like to dedicate this thesis to my wife Deborah Ann who never ceased to provide support and encouragement as well as presenting me with a wonderful daughter Gillian Marie on 16 October, 1985. Gillian has contributed to this thesis with her amazing talent for deleting documents from disks and trashing hard copies as fast as her father could print them. Additional production assistance was willing supplied by Kyle Russell, born 29 November, 1987. He, like this, represent the last draft.

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INTRODUCTION

The Middle Ordovician of southeastern Minnesota is represented by rock formations within the Tippecanoe sequence, an early Paleozoic (middle Ordovician to Silurian) cycle of transgressive-regressive marine sedimentation. The Tippecanoe sequence consists of sandstones, siltstones, shales and carbonates deposited in the most extensive epeiric sea of the Phanerozoic Era (Elias, 1983). The initial onlap of the Tippecanoe transgression was recorded in five formations, in chronostratigraphic order: St. Peter, Glenwood, Platteville, Decorah, and Galena. The initial period of carbonate sedimentation is represented by the Platteville Formation.

The Platteville is a thin (3 to 12 meters) carbonate formation which characteristically has thin to medium bedded lime mudstone, wackestone, or packstone alternating with thin interbeds of shale. Within Minnesota, three members of the Platteville are recognized, in chronostratigraphic order: the Pecatonica, a fossiliferous, sandy, medium to thickly bedded, dolomitic limestone; the McGregor, a fossiliferous, irregular wavy, thin to thickly bedded, dolomitic limestone; and the Carimona, a fossiliferous, medium to thickly bedded limestone. Notable within the Carimona member is the widespread and easily recognized Deicke (Carimona) bentonite ash layer.

Previous research on the Platteville Formation in Minnesota has been extensive in the areas of lithology, stratigraphy, and paleontology. However, no study has investigated the formation's trace fossils (ichnofossils) except to note

the presence of "worm burrows" or "fucoids." Marine carbonates contain facies as diverse as marine sediments of terrigenous clastic origin. The trace makers were certainly equally numerous and diverse in both realms. The same cannot be said for the number of ichnologists who have shown a marked preference for clastic sedimentary units. This is explained partially because of the exceptional detail preserved in trace fossils from clastic sediments, and possibly because as noted by Kennedy (1975) trace fossils are generally less conspicuous and more difficult to study in carbonates.

OBJECTIVES

Prior to the start of this research, three major goals were: (1) to locate, identify, and catalogue the trace fossils found within the three members of the Platteville Formation in southeastern Minnesota; (2) to make a detailed examination of the limestone beds bounding the Deicke bentonite horizon and the trace fossils contained within; (3) to apply the ichnological data obtained to a paleoenvironmental analysis of the Platteville Formation during the time of its deposition within the Hollandale Embayment. Again, special emphasis was placed upon the Carimona member and the bedding units containing the bentonite ash bed. In a transgressive sea, it is generally not possible to state that a bed, though continuous throughout a region, is time equivalent unless parallel to depositional strike (Shaw, 1964). The use of the isochronous

bentonite horizon as a marker should allow the closest approximation possible to time equivalent beds.

LOCATION AND EXTENT OF THE STUDY AREA

The study area contains approximately 10,000 square kilometers (4000 square miles) in southeastern Minnesota, extending from Minneapolis to the Iowa border (Figure 1). A detailed study was made of the area southeast of a line from Cannon Falls to Northfield, Minnesota. North of that line, in Hennepin, Ramsey, and Dakota Counties, a more cursory examination was made of several outcrops.

Outcrops were located by information obtained from a variety of sources. Included were the geologic field guides for the region by Schwartz and Sloan (1956), Swain and Austin (1969), Sloan (1972), Darby and Webers (1979), unpublished Master's theses by Majewske (U of M, 1953), Ford (U of M, 1958), Hoeft (U of M, 1959), and the published Ph.D. thesis of Weiss (U of M, 1957). Also useful were the Minnesota Geological Survey Bulletin by Stauffer and Thiel (1941), the geologic field map by Sloan and Austin (1966), and the Report of Investigation by Mossler (1985).

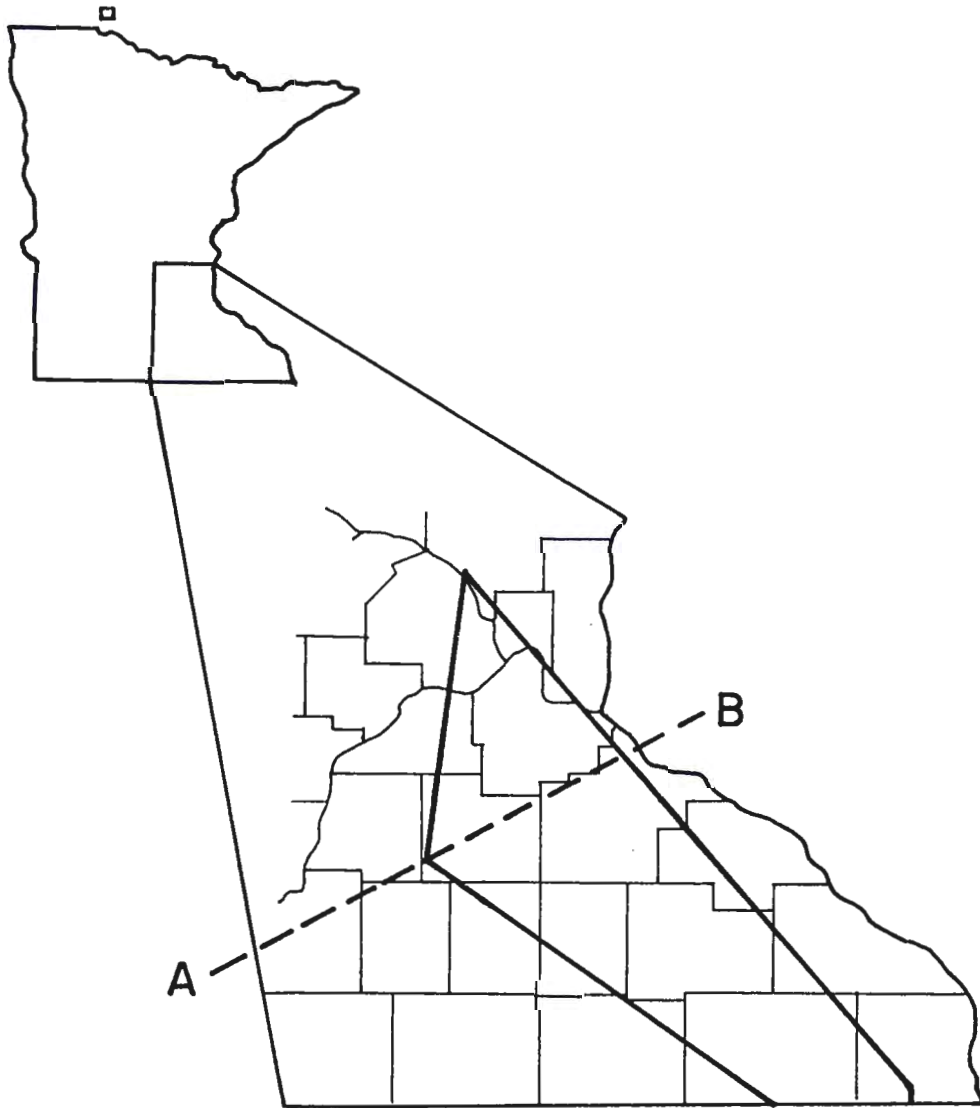


Figure 1 - Area of investigation of Platteville ichnology. Line A-B runs through Northfield and Cannon Falls, Minnesota. See Appendix III for outcrop locations.

METHODS OF STUDY

Field Methods

The investigation included field work to observe and photograph all types of trace fossils found in the Platteville, with special attention to the Deicke bentonite horizon. Where possible, a sample of each trace fossil was obtained for laboratory study, as were samples of the limestone beds bounding the Deicke bentonite. The carbonate classification system proposed by Dunham (1962) was used in this study.

Laboratory Methods

In the laboratory, photographs of all varieties of trace fossils were taken using both color slides and black and white prints. Where contrast enhancement was required, ammonium chloride was used to smoke the specimens.

In order to determine the morphology of different traces, several hundred cuts were made in limestone samples using a diamond saw. In some cases a simple clean face was cut, while others required the complete serial sectioning of the sample.

Where required limestone slabs were stained to distinguish between calcite and dolomite, following the procedure suggested by Friedman (1959). Slabs were etched in a 10% solution of hydrochloric acid for approximately 2 minutes. The etched slabs were then stained for calcite using a solution of 0.2 gm of

Alizarine Red dissolved in 100 ml of hydrochloric acid. The slabs were placed in the solution for 30 to 45 seconds, then rinsed in running water. The presence of calcite was indicated by a reddish pink color.

Acetate peels were made on polished slabs where textural data were required using the techniques suggested by Buehler (1948). The slabs were etched for 15 to 20 seconds in a 5% solution of hydrochloric acid, rinsed under running water and allowed to dry. The etched surfaces were then saturated with acetone and a precut piece of 0.076 mm frosted art acetate was placed, frosted side down, upon the surface and pressed into it. After approximately 2 hours the acetate peels were then removed from the slabs for examination.

Limestone slabs from most beds bounding the Deicke bentonite, as well as other beds where burrow morphology could not be determined, were examined by x-ray. The exposure techniques followed were those suggested by Fraser and James (1969). The results of most x-rays were of little value owing to limited density contrast within most limestone from the Platteville; however, in a few cases it proved to be very helpful in morphology determination.

GENERAL STRATIGRAPHY, LITHOLOGY, AND PALEONTOLOGY OF THE LOWER TIPPECANOE SEQUENCE

The lower Tippecanoe sequence consists of four recognized formations of different lithologies. In southeastern Minnesota the stratigraphic thickness of the sequence is approximately 50 meters.

St. Peter Formation

The St. Peter Formation is a fine to medium grained quartzarenite consisting of very mature, subrounded to rounded white siliceous grains, many of which are frosted. Deposition has been attributed, in part, to eolian dunes (Dott and Byers, 1980), beaches (Fraser, 1976), and large scale submarine sand waves (Pryor and Amaral, 1971).

Fossils are sparse within the St Peter, consisting of pelecypods, gastropods, and cephalopods (Webers, 1972). Trace fossils in the form of vertical pyritized Skolithos and Diplocraterion burrows are present within the formation (Figure 2).

Glenwood Formation

The Glenwood Formation was deposited conformably upon the St. Peter. The contact between the two formations is gradational and is generally placed above the uppermost massive white sandstone bed in the St. Peter and below the first argillaceous poorly sorted sandstone at the base of the Glenwood (Austin, 1972). Consisting of gray, grayish-green, and yellow shale, the Glenwood contains considerable sand from the underlying St. Peter. The Glenwood is believed to be either a shallow marine shelf deposit (Ostrom, 1970), an extensive coastal lagoon deposit (Fraser, 1976), or an offshore transgressive facies (Schutter, 1978).



Figure 2 - Vertical pyritized (A) Skolithos and (B) Diplocraterion burrows in the St. Peter, Nerstrand road cut.

Fauna within the Glenwood consists of pelecypods, gastropods, cephalopods, brachiopods, bryozoans, pelmatozoans, echinoids, conularids, trilobites, ostracodes, scolecodonts, and conodonts (Schutter, 1978). Trace fossils consist of gently inclined to vertical dwelling-type burrows (Figure 3). The entire formation is extremely bioturbated, as indicated by the lack of laminations (Moore and Scrutton, 1957; Pryor and Amaral, 1971; Heckel, 1972; Byers, 1974; Howard, 1978).

Platteville Formation

The Platteville Formation was deposited conformably upon the shales of the Glenwood, offshore where biogenic sedimentation dominated clastic. In some locations the two formations intertongue because of the local influx of nearshore sediments. The contact between the two formations is placed above the last massive shale bed and below the first thickly-bedded, sandy, dolomitic limestone of the Platteville's Pecatonica Member (Austin, 1972).

The Platteville's composition ranges from a fossiliferous lime-mudstone to a fossiliferous lime-wackestone. Contained within some beds are thin zones of fossiliferous lime-packstone that may be laterally persistent. Dolomite is common in the Pecatonica and McGregor Members of the Formation.

Interbedded shales are common in the Platteville, becoming increasingly prominent in the Carimona Member (Figure 4). These shales are the result of either an influx of siliceous clastic sediments or the settling out of silt and clay

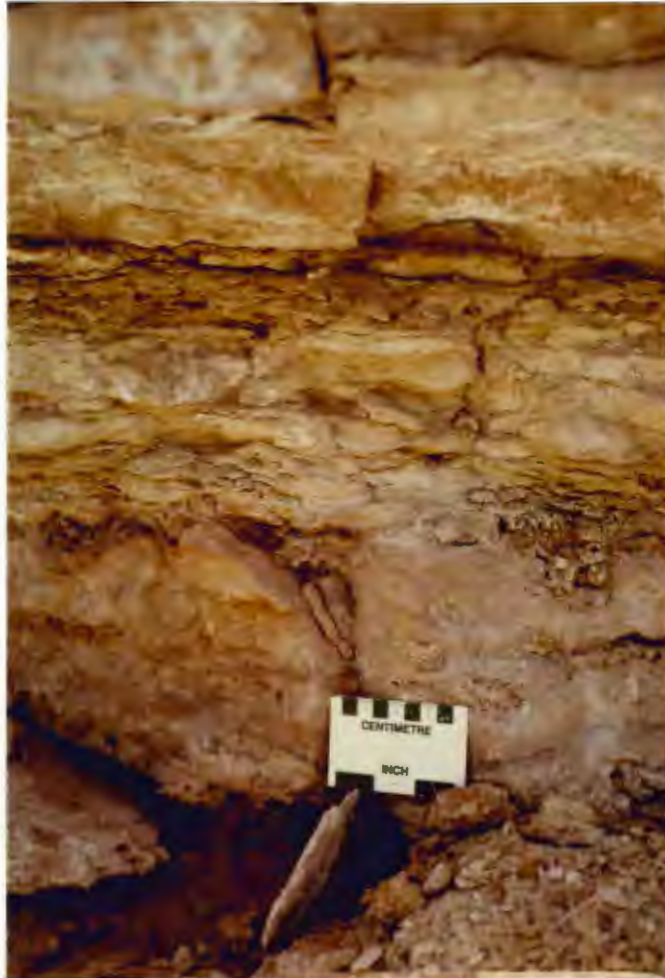


Figure 3 - Inclined dwelling-type burrow common in the Glenwood, south Fountain road cut.



Figure 4 - Carimona Member of the Platteville and the overlying Decorah Formation. The clipboard rests below the Deicke bentonite, the pickhead (upper left) below the Decorah bentonite while the end of the handle is just above the uppermost limestone bed in the Carimona Member.

sized particles after their resuspension by wave or current generated turbulence. Austin and Parham studied the relative amounts of montmorillonite and illite clays in the shales of the Glenwood (1967) and Decorah (1969) Formations. Their research determined that the clastic source for these shales was the transcontinental arch to the west and southwest, a conclusion supported by Bretsky et al. (1977) but questioned by Schutter (1978). Hoeft (1959) found no essential difference between the shales of the Carimona Member and the overlying Decorah Formation. This interval is thought to represent a shallowing of the waters. The Deicke bentonite will be discussed later.

The Platteville fauna is far more abundant than that of either the St. Peter or Glenwood Formations. Dominating the bottom was a sessile benthonic community, predominantly of articulate brachiopods; most notable are members of the genera Pionodema, Protozyga, and Strophomena (Webers, 1972). The inarticulate brachiopod Lingula (sensu lato), trilobites, gastropods, pelecypods, conodonts, and graptolites are also represented within the formation. Cephalopods are diverse and numerous in the Platteville (Webers, 1972). Especially prominent are members of the genus Endoceras. In the Carimona Member, bryozoans are first observed in the Platteville bottom community. Trace fossils are numerous and diverse in the formation and are discussed in the body of this paper.

Decorah Formation

The Decorah Formation rests conformably upon the Platteville. The contact between them is placed below the lowest non-coquinoid carbonate bed (Austin, 1972). In some locations it is necessary to simply place the contact where shales clearly dominate carbonates.

The Decorah consists of a blue-green fissile shale deposited during a regression which marked the end of the Tippecanoe sequence's initial onlap. That high energy conditions existed at intervals is demonstrated by ripple marks as well as by layers of coquinoid limestone (Weiss, 1957; Webers, 1972). However, non-turbid waters of normal salinity were also present as demonstrated by a bottom community dominated by bryozoans and brachiopods.

DEVELOPMENT OF PLATTEVILLE NOMENCLATURE

The development of Platteville nomenclature has received exhaustive treatment by previous researchers. For that reason, only the most general coverage is given here, with the object of supplying references to those who may wish to examine the nomenclature's development in more detail. One is especially directed to the works of Majewske (1953) and Weiss (1957) for the early development, while Austin (1972) and Mossler (1985) include more recent changes.

The Platteville Formation received its name from the type section at Platteville, Grant County, Wisconsin (Bain, 1905). The formation was originally defined to include all the exposed shale and limestone between the St. Peter and Galena Formations. This definition supplanted earlier work by Winchell (1873), Sardeson (1896, 1897) as well as Winchell and Ulrich (1897).

Use of the name Platteville was restricted to the central limestone unit of the type section (Calvin, 1906). This name was adopted as a formational name by the United States Geological Survey in 1910. Subsequent researchers redefined the formation's boundaries and subdivided it into various members based on both lithology and faunal content (Kay, 1928, 1935; Stauffer and Thiel, 1933, 1941; Bays and Raasch, 1935).

The Minnesota Geological Survey (Austin, 1972; Mossler, 1985) recognizes three formal members for the Platteville in southeastern Minnesota, they are in chronostratigraphic order: the Pecatonica (Hershey, 1897), the McGregor (Trowbridge, 1935), and the Carimona (Weiss, 1955). In the Twin Cities area the McGregor Member is replaced by three submembers: the Mifflin (Majewske, 1953), the Hidden Falls (Sloan, 1956), and the Magnolia (Majewske, 1953).

GEOLOGIC HISTORY

During the early to middle Paleozoic, a series of marine transgressions inundated much of the North American craton. In southeastern Minnesota these transgressions were responsible for the deposition of approximately 615 meters (2000 feet) of shallow marine sediments within the Hollandale Embayment. This embayment was bounded on the west and north by the Transcontinental Arch, to the east by the Wisconsin Arch and to the south by the Forest City (Central Iowa) Basin of which it was a northern projection (Figure 5).

The Hollandale Embayment is underlain by a basement of Precambrian rocks of granitic and basaltic composition. Faulting of the basement complex during the late Precambrian occurred along the axis of the mid-continent gravity high, a failed rift zone forming a graben into which Paleozoic sediments were deposited (Sims and Morey, 1972). During the Paleozoic, fault movement may have amounted to several hundred feet of vertical displacement, and provided topographic source areas for clastic sediments (Sloan and Danes, 1962; Morey and Rensink, 1969; all in Austin, 1972). Cambrian clastic sources were primarily from the east (Webers, 1972), while Ordovician sources were dominantly from the Transcontinental Arch to the west (Austin and Parham, 1967, 1969).

The sediments within the Hollandale Embayment are divided into seventeen formally defined formations beginning with the upper Cambrian Mt. Simon Sandstone through the Devonian Cedar Valley Limestone. Within these

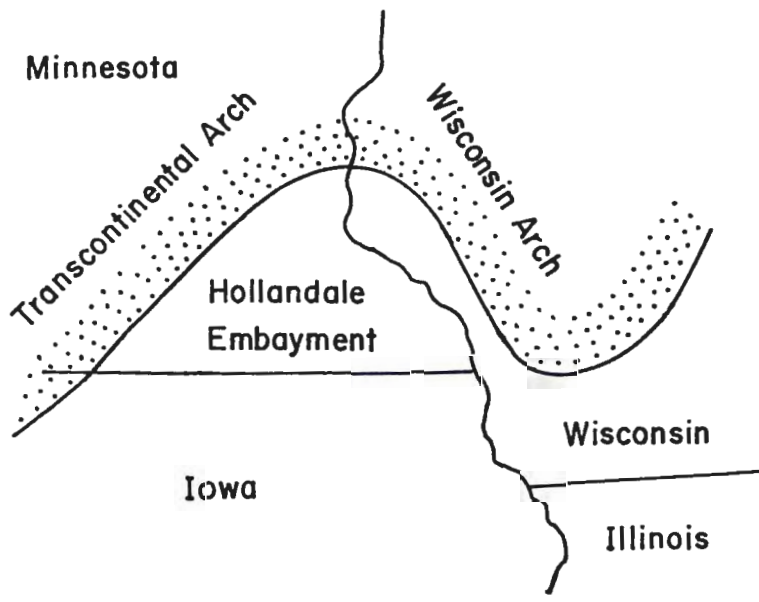


Figure 5 - The location of the Hollandale Embayment, Transcontinental Arch, and Wisconsin Arch in Minnesota, Wisconsin and Iowa.

formations, Austin (1970) recognized nine full or partial cycles of marine sedimentation. Each cycle, originally applied to Cambrian-Ordovician sediments of the upper Mississippi River Valley (Ostrom, 1964), consists of four successive environments of deposition, each defined by a lithotope typical of that environment. These lithotopes are: (1) well-sorted quartzarenite; (2) poorly-sorted units of mixed lithologies; (3) shale or argillaceous sandstone; and (4) carbonate rocks. A significant trend observed in these formations is the diminishing abundance of sandstone and the increasing abundance of carbonates throughout the time of Hollandale sedimentation (Austin, 1970, 1972).

The Tippecanoe sequence (Middle Ordovician to Silurian), a marine incursion that extended up from the Oklahoma Basin (Ross, 1976), began with the deposition of the St. Peter Sandstone. The point of maximum transgression is represented by the upper Galena Formation (Mossler, 1985). The sequence of sedimentation which includes the Platteville Formation coincides with the initial onlap of the Tippecanoe sequence (Figure 6).

At the time of the Tippecanoe transgression, the area of the Hollandale Embayment was located geographically south of the equator (Figure 7). The waters of the region were warm and shallow and were subject to a relatively constant trade wind direction from the southeast (present east).




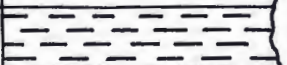


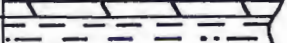


Formation	Member	Litology
Galena	Stewartville	
	Prosser	
	Cummingsville	
Decorah		
Platteville	Carimona	
	McGregor	
	Pecatonica	
Glenwood		
St. Peter		

Figure 6 - Stratigraphy and lithology of the initial onlap of the Tippecanoe sequence (adapted from Webers, 1972).

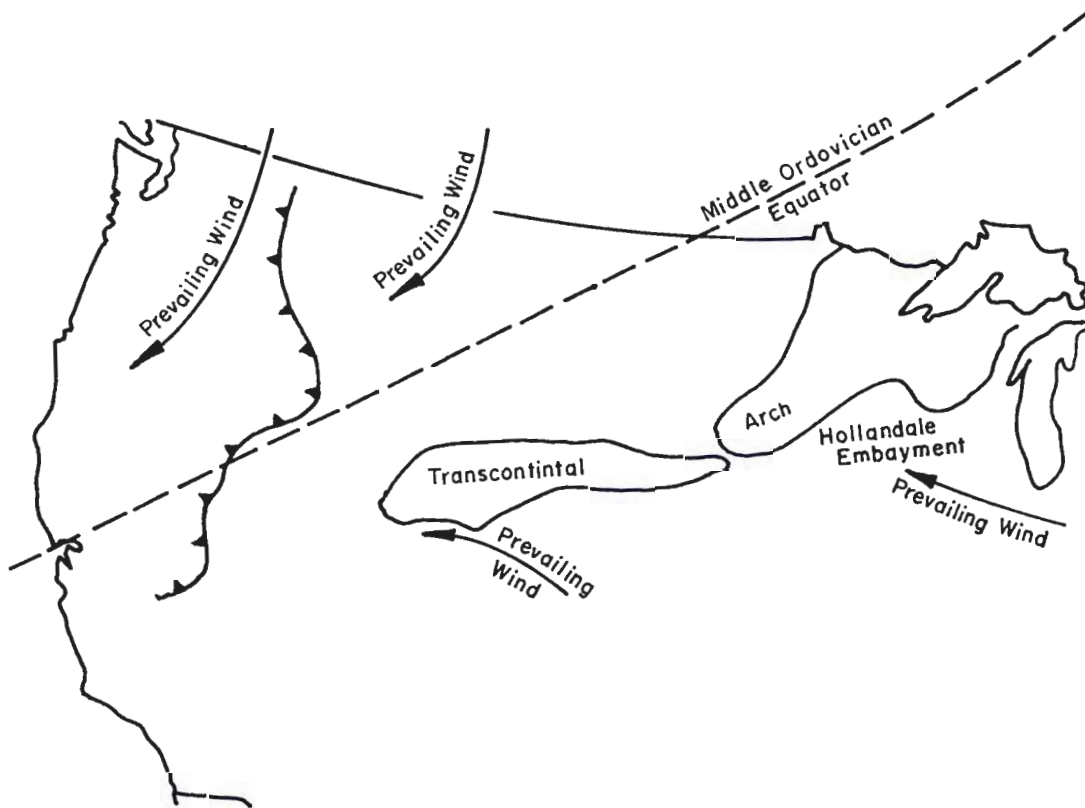


Figure 7 - The geographic position of the Hollandale Embayment, the equator, and the paleowind direction at the onset of the Tippecanoe transgression in the Middle Ordovician (modified from Ross, 1976).

ICHOLOGY

Ichology is commonly defined as the study of tracks, trails, burrows, borings and other traces made by organisms (Frey, 1975). During the past three decades trace fossils have been applied to a multitude of geologic problems (Appendix II: Table 1), ranging from Precambrian metazoan life and the Precambrian-Cambrian boundary (Glaessner, 1969; Banks, 1970; Bergstrom, 1970; Crimes and Anderson, 1985) to bathymetry and paleoenvironment (Farrow, 1966; Chamberlain, 1971; Fursich, 1975).

Much of the importance of trace fossils is based upon three features which are not totally shared with body fossils. Individual ichnogenera and ichnospecies tend to exist for long periods of geologic time, thus are valuable for comparisons of traces and environments from different times. Also, many genera and species display a preference for a very narrow environmental facies range. Finally, traces are almost inevitably located in situ due to an inability to survive transportation en toto.

The study of trace fossils (lebensspuren) entails their description, classification and interpretation (Simpson, 1975). The schemes for those purposes are numerous, reflecting the disparity between "lumpers and splitters" throughout geology. However, most of these are modifications of schemes proposed by Adolf Seilacher in a series of articles throughout the 1950s and 1960s.

Toponomic

Classifications stressing the origin, configuration, and preservation of trace fossils are an important part of ichnology (Frey, 1973). Used here is the toponomic classification of Seilacher (1953, 1964a, 1964b) which emphasizes the position of the trace within the sediment and not the location of the trace-maker (Figure 8).

Behavioral

Recognition of the behavior exhibited by the organism is the most critical criterion for work in the areas of facies analysis and sedimentation (Frey, 1973). Trace fossils record behavior as constant dynamic interactions among benthic organisms and between organisms and the environment. Seilacher's (1953) behavioral (ethological) classification has been employed here (Figure 9). An explanation of the behavioral categories is included in Appendix II: Table 2.

Ichnofacies

Seilacher (1967) proposed that bathymetry was the chief environmental factor controlling trace fossil communities and erected six adjacent trace fossil facies ranging from non-marine to abyssal (Figure 10). Some trace fossils originally proposed as depth indicators have proved very unreliable (Osgood and Szmuc, 1972; Xian-Tao Wu, 1982) while even the best are not absolutely valid (Crimes, 1977). More recently, Byers (1982) has argued that animal

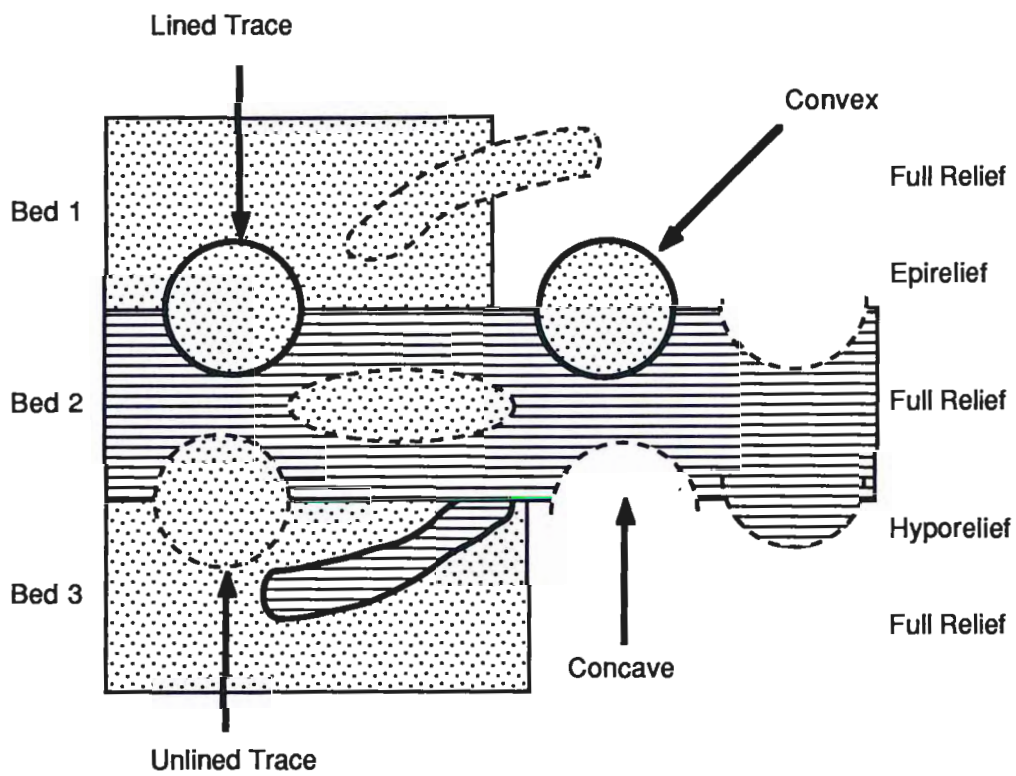


Figure 8 - Preservational classification scheme devised by Seilacher (1953, 1964a, 1964b).

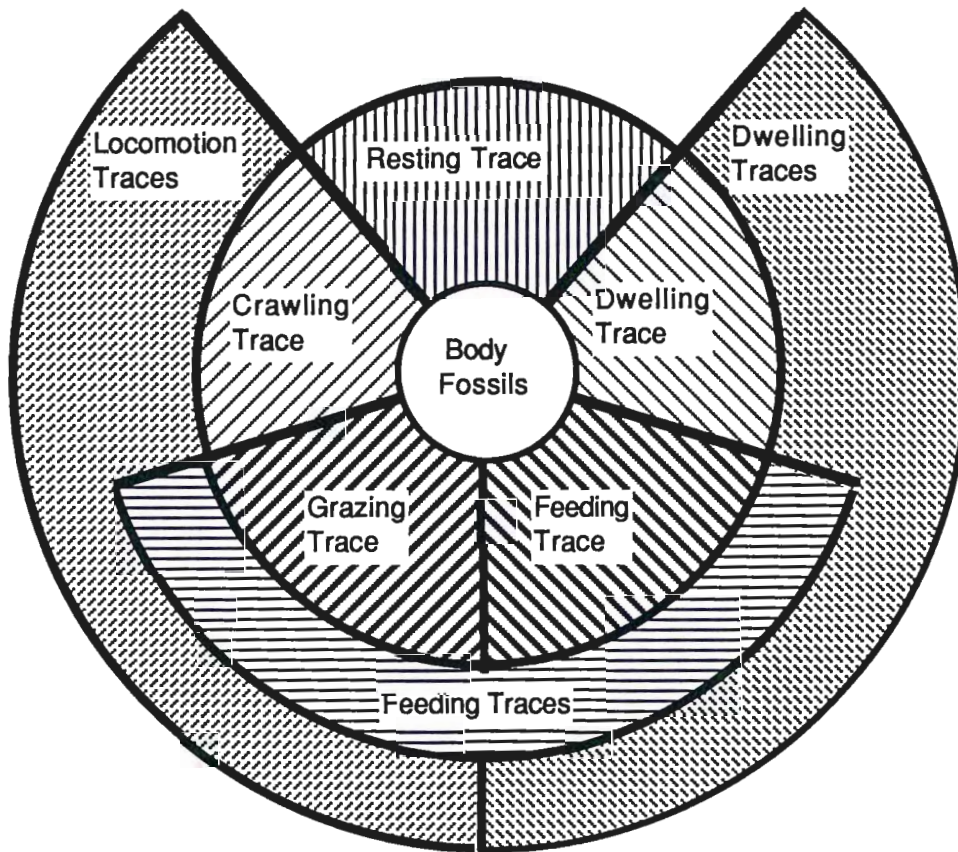


Figure 9 - Behavioral (ethological) classification devised by Seilacher (1953). The sixth and overlapping category, escape structures (fugichnia) is not depicted.

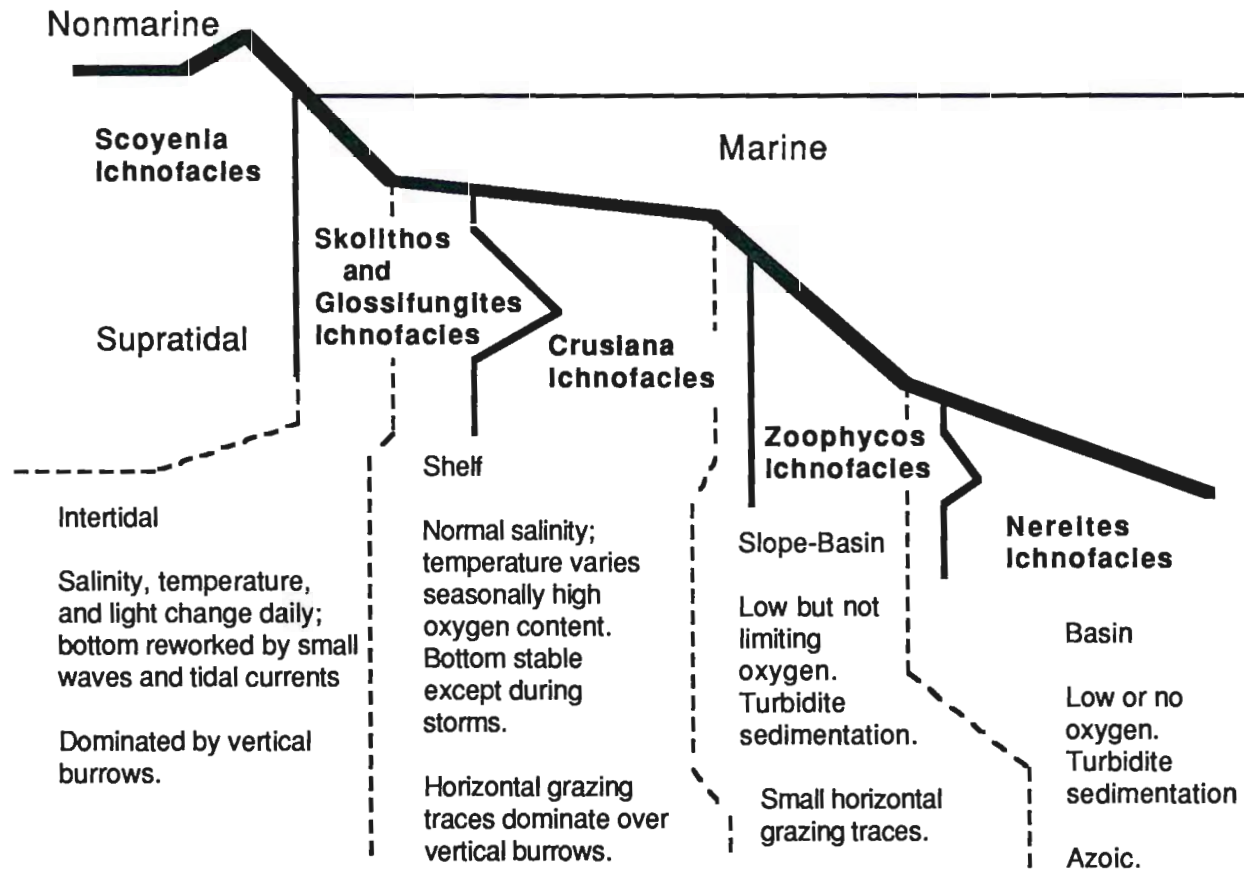


Figure 10 - Ichnofacies (Seilacher, 1964, 1967) and important general ecologic parameters (Rhoads, 1975).

distribution and physical energy may be more valid criteria for ichnofacies determination, and that many of the basic tenets should be reconsidered.

It is my opinion that a broad view of ichnofacies is most appropriate. Ichnofacies represent an assemblage of trace fossils which record the constant dynamic interactions among benthic organisms and between organisms and substrate. The substrate imposes limits upon the organisms, which in turn modify the substrate (Gray, 1974; Howard and Frey, 1973; Frey and Seilacher, 1980). The animal populations, behaviors, and substrate characteristics involved are determined by a wide range of physical and biological factors including bathymetry, physical energy (hence hydrodynamic conditions), nutrients, oxygen, salinity, suspended sediments, turbulence, and temperature.

Note on Ichnofossil Taxonomy

Binary nomenclature applied to trace fossils has not had official sanction since the 1930s. Trace fossil genera and species should be based (ideally) strictly upon the morphology of the biogenic structure, without regard to the biological genera and species of organisms which formed them. Therefore a trace fossil genus or species may be formed by more than one biological genus or species of organism while conversely, different ichnogenera or ichnospecies of traces may be formed by the same biological species of organism (Frey and Seilacher, 1980).

PRESERVATION AND OCCURRENCE OF TRACE FOSSILS

The diverse Platteville trace fossil assemblage is not without bias. Because of preferential preservation, the trace fossil assemblage is dominated by the record of infaunal rather than epifaunal organisms. The record of epifaunal organisms was less apt to be preserved because of erosion, subsequent bioturbation, and the special requirement of a covering blanket of contrasting lithology, (i.e., lime mud to siliceous mud) in order to be preserved in observable form. Without a change in lithology, the traces would be contained totally within the homogeneous limestone bed, without the necessary contrast for microrelief to be observable. If a change in lithology did occur, then the traces in either convex or concave epirelief would be buried by a medium which would allow the preservation of microcontacts (Figure 8).

Individual burrows of infaunal organisms completely contained within limestone beds were far less detectable than those which penetrated a subjacent bedding plane. Infaunal traces formed along a limestone-shale bedding plane are preserved in convex or concave hyporelief. Such infaunal traces are far more common than epifaunal traces because they were shielded from erosion, resistant to erosion, or subject to less intense disturbance by shallow bioturbation. Some horizons were simply more easily observed because of bedding characteristics conducive to bedding plane exposure.

Two bedding characteristics, thickness and continuity, were found to be of particular importance in contributing to the amount of trace exposure. Traces

on the vertical faces of beds were uncommon; however, when present they were more likely to be observed where the limestones were medium to thickly bedded. More important was the flatness of bedded horizons; such bedding planes were far more likely to display traces as (usually convex) hyporelief. Uneven, wavy, or nodular bedding typical in the McGregor Member, generally displayed far fewer trace fossils.

Exposed even bedding planes provided the vast majority of observations of trace fossils. Active rock quarries with relatively freshly exposed vertical sections and abundant float blocks were the major location of exposed bedding planes. Commonly it was possible to attribute the displaced blocks to their original bedding units, or at least to the proper member, with a high degree of certainty. The majority of these blocks were from the Carimona Member because blocks derived from lower in the section were buried by successive talus accumulation from above as a result of blasting.

At road cuts and in abandoned quarries large float blocks are less common; however, differential weathering of interbeds had resulted in overhangs exposing in situ bedding planes. Generally, the best exposed in situ bedding plane was the limestone bed directly above the Deicke bentonite. The bentonite has weathered recessively markedly faster than shale interbeds of comparable size. Thin shale weathered less than thicker shale interbeds, resulting in the poorest bedding plane exposures.

THE PLATTEVILLE ICHNOASSEMBLAGE

The ichnoassemblage of the Platteville Formation exhibits a considerable degree of diversity with 23 ichnospecies divided among 20 ichnogenera as well as 3 types placed within problematica as unidentified. The identified ichnogenera include: Arenicolites, Bifungites, Chondrites, Conostichus, Cylindrichnus, Diplichnites, Fustiglyphus, Gyrolithes, Lingulichnus, Muensteria, Nereites, Palaeophycus, Planolites, Rhizocorallium, Rusophycus, Subphyllochora, Teichichnus, Thalassinoides, (?)Torrowangea and Trypanites. The distribution of these ichnogenera among major field locations in southeastern Minnesota is shown in Table 1. Two additional genera, Diplocraterion and Skolithos are found in the subjacent St. Peter and Glenwood Formations. Descriptions of individual ichnospecies and ichnogenera can be found in Appendix I (Systematic Ichnology).

Examination of the assemblage reveals a number of forms which are facies-specific to the subtidal shelf environment (shallow inshore to deeper offshore). Included are Diplichnites, Muensteria, and Rusophycus, as well as Bifungites which is restricted to the intertidal to shallow offshore. Several other forms are facies-variable but are reported most often from water of shallow to intermediate depth: Arenicolites, Conostichus, Fustiglyphus, Gyrolithes, Lingulichnus, Rhizocorallium, Subphyllochora, Teichichnus, and Thalassinoides. One form, Nereites, is facies-variable usually in the direction of deeper water. Two very common forms Chondrites and Planolites as well as

TABLE 1
 Distribution of Ichnogenera among the major field locations in the Platteville Formation.
 Location numbers correspond with the location descriptions in Appendix III.

(C) Carimona Member (M) McGregor Member (P) Pecatonica Member (A) All Members Present (F) Float

Genera	Location	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
<u>Arenicolites</u>								C		C	C	C				C						C	C	C					
<u>Bifungites</u>			C		C											C		C											
<u>Chondrites</u>		A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
<u>Conostichus</u>				C		F																C							
<u>Cylindrichnus</u>			C				M			C					C			C				M	C	F	F				
<u>Diplichnites</u>			C																					C					
<u>Fustiglyphus</u>										C									C										
<u>Gyrolithes</u>										C										C									
<u>Lingulichnus</u>			C		C		C	C	C	C								C	C					C	C				
<u>Muensteria</u>						F																C							
<u>Nereites</u>			C	F						C																			
<u>Palaeophycus</u>					M					C						C	F									CF			
<u>Planolites</u>		C	C	A	A	MF	A	A	CM	A	A	A		P		C	CM	C	A	M	C	CM	A	CM	C	C	C	M	MP
<u>Rhizocorallium</u>		C								C				C	C	C						C							
<u>Rusophycus</u>					F	F										C								C					
<u>Subphyllochorda</u>																								C		C			
<u>Teichichnus</u>					CM										C		C					F			C				
<u>Thalassinoides</u>		C	C		CF	M				C	C		C						C	C			F						
<u>(?)Torrowangea</u>																									C	C			
<u>Trypanites</u>		P	P	P	P		P									M				F			M						

the far less common Palaeophycus normally exhibit very wide facies ranges. Generally the Platteville ichnoassemblage is equivalent to the Cruziana ichnofacies of Seilacher (1964, 1967) possessing a relatively high population density and diversity while dominated by infaunal deposit and suspension feeders.

The majority of genera will be referred to only in Appendix I. Several others are given brief coverage here because of some facet of note, while other traces dominate the discussions.

THE CLASSIC CRUZIANA

The Cruziana ichnofacies is characterized by the activities of trilobites. Trilobite trace fossils are generally considered synonymous with the subtidal shelf environment. Two traces found in the Platteville, Diplichnites and Rusophycus, are attributed to trilobites. Of these Diplichnites is a locomotion trace (Figure 11) while Rusophycus is a resting trace (Figure 12). The number of trilobite traces observed was not consistent with the markedly greater number of body fossils which usually consisted of molted pygidia. While molted exoskeletal parts give the impression of a larger population than was actually present, the disparity is real and attributed to the poor preservation of epifaunal traces.

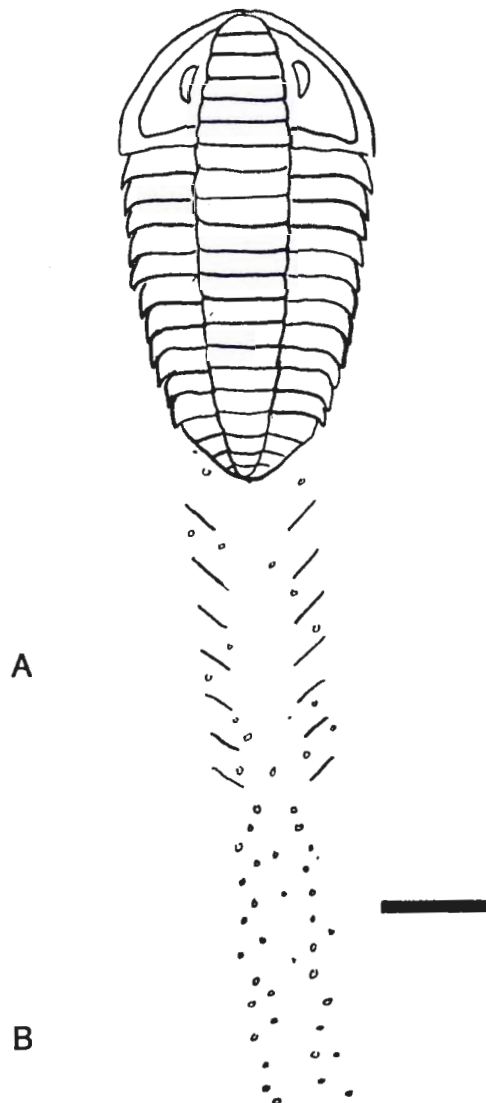


Figure 11 - Diplichnites, a locomotion trace formed by trilobites. (A) During movement (B) Stationary Bar scale = 1 cm

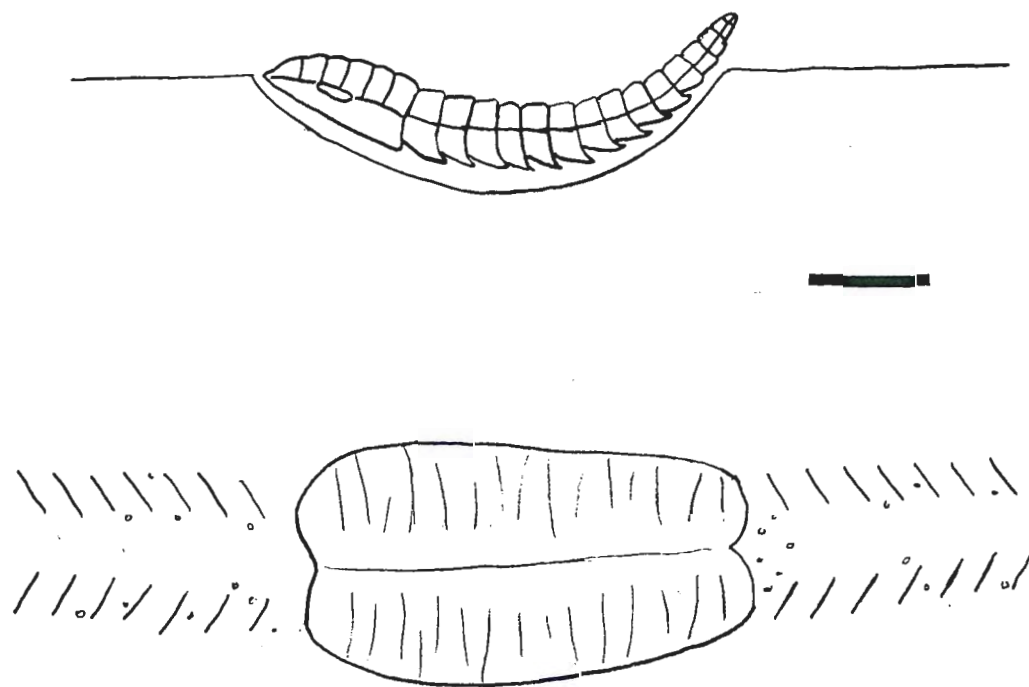


Figure 12 - Rusophycus, a resting trace formed by trilobites. Upper: Side view
Lower: Top view Bar scale = 1 cm

DOMINANT AND IMPORTANT ICHNOGENERA

Chondrites

One ichnogenus, Chondrites, dominates the trace fossil assemblage within the Platteville. Chondrites is ubiquitous vertically and laterally throughout the Platteville. Present in all horizons, Chondrites may be locally dominant to the exclusion of all other genera. The Platteville contains two observed Chondrites species differentiated on the basis of burrow diameter, the smaller ranging from 0.5 to 2.0 mm and the larger from 4.0 to 6.0 mm. Each remains distinct within an individual burrow system. The two forms are commonly found in close association. Simpson (1957), Sellwood (1970), Stasko (1974), and Shourd and Levin (1976) have noted a similar bimodal size distribution which was attributed by Simpson, and Shourd and Levin to two species of organism. If the burrows were the result of different stages of growth in a single organism, an intermediate size burrow would be expected. The lack of such an intermediate supports the two species origin for Chondrites burrows.

The burrows consist of closely grouped vertical shafts which soon become dominantly horizontal and dendritic in configuration (Figure 13). The burrows commonly display third order branching, and fourth or fifth order branching are not uncommon. The angle of branching ranges from 30 to 45 degrees. There is no interpenetration between branches of the same burrow system (phobotaxis), however, intersection with other burrows is noted. For comprehensive coverage of the genus Chondrites, refer to the work of Simpson (1957).

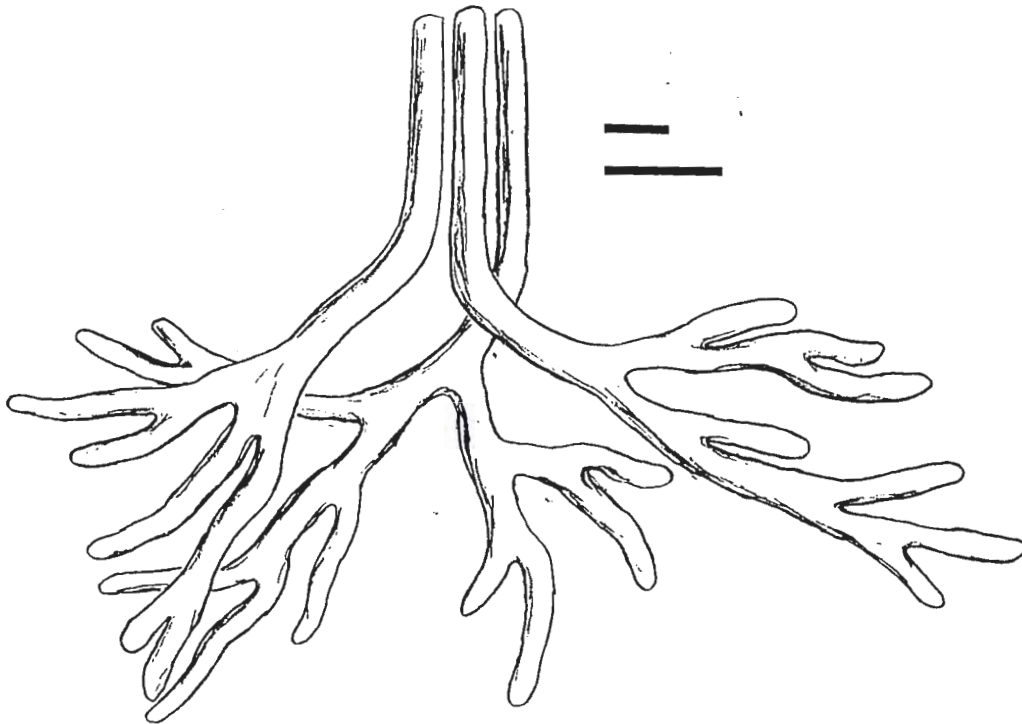


Figure 13 - Dendritic burrow configuration of Chondrites. The two bar scales, short and long (= 1 cm), refer to the large and small forms of Chondrites, respectively.

Bifungites

The most important ichnogenus observed in the Platteville is Bifungites. The trace consists of a vertical U-shaped burrow which has a spherical chamber at the base of each of the two vertical shafts (Figure 14). All specimens are preserved in convex hyporelief and display the dumbbell configuration commonly observed in the ichnogenus.

Bifungites has been reported from intertidal or near-intertidal Devonian strata in western Montana (Rodriguez and Gutschick, 1970; Gutschick and Lamborne, 1975), in interbedded shale and siltstone of the Upper Devonian in Ohio and Pennsylvania (Szmuc, Osgood, and Meinke, 1976), in limestone of the Middle Ordovician in Quebec, Canada (Pickerill and Forbes, 1977), in the tidal and offshore facies of Devonian strata of New York (Miller, 1979), a transitional environment between the shoreface zone and the nearshore shelf of the Carboniferous in Libya (Turner and Benton, 1983), and in the Cruziana ichnofacies in the Lower Cambrian of Pakistan (Seilacher in Turner and Benton, 1983). Bifungites has not been reported from sediments considered to have been deposited any deeper than the shallow subtidal shelf. Platteville specimens all occur in the Carimona Member, including strata just above the Deicke Bentonite.

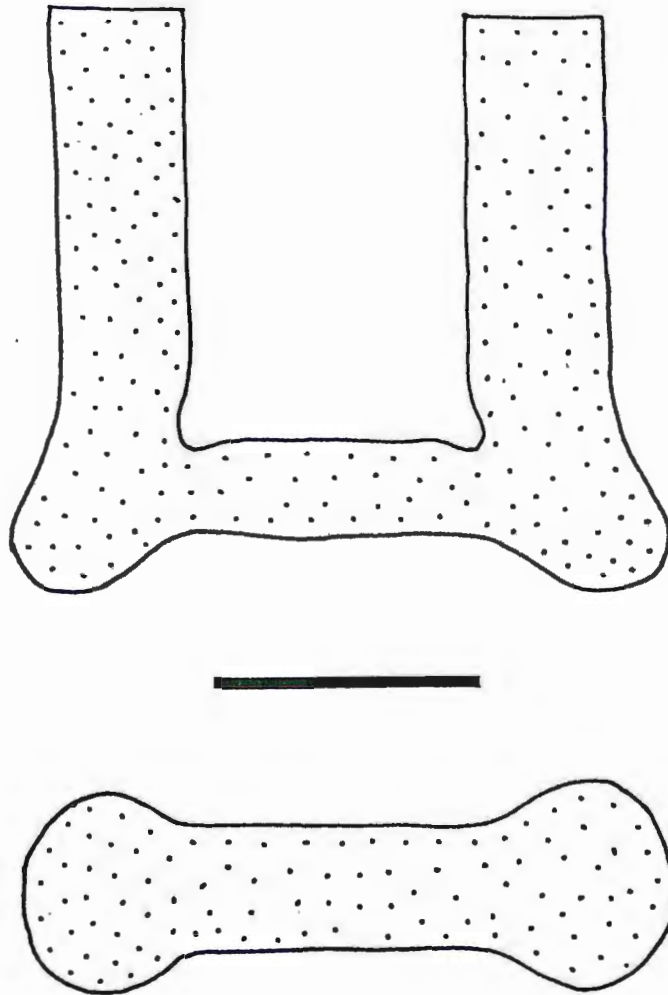


Figure 14 - Bifungites Upper: In a vertical cross section. Lower: As seen in convex hyporelief. Bar scale = 1 cm

Lingulichnus

Lingulichnus is the recently named burrow of inarticulate linguloid brachiopods (Hakes, 1976), a group which has been an important element in the nearshore community since the Ordovician (Bretsky, 1969). Lingulids have been considered "in situ" if the valves are articulated and oriented vertically or at high angle to the bedding, and/or the pedicle or burrow is preserved (Paine, 1970; Pemberton and Kobluc, 1978; Cherns, 1979) (Figure 15). Paleozoic in situ lingulids are common in clastic sediments; however, occurrences from soft-bottom carbonate substrates are rare. Pickerill (et al., 1983) noted that in situ lingulids are not restricted to clastic sediments, and can be equally common in soft-bottom carbonate substrates. In addition, the preserved burrows of lingulids are rare throughout the geologic column (Pemberton and Kobluc, 1978; Cherns, 1979; Pickerill, Harland, and Fillion, 1983).

Platteville specimens of Lingulichnus verticalis are tongue-to-spade shaped burrows commonly oriented within 10 degrees of vertical. The widest dimension is at the top, which is elliptical in transverse section. In some burrows a smaller diameter basal stem with a circular transverse section is present (Figure 16). Commonly Lingulichnus verticalis is observed to contain the original lingulid (Figure 17). These lingulids are identified at the generic level as Lingula, specific identification is generally not possible since only the external shells are preserved. Lingula first appears in the Platteville stratigraphic record in the lowermost sediments of the Carimona Member and rapidly



Figure 15 - Inarticulate brachiopod Lingula, in situ in limestone bed directly over the Deicke bentonite, White Rock road cut.

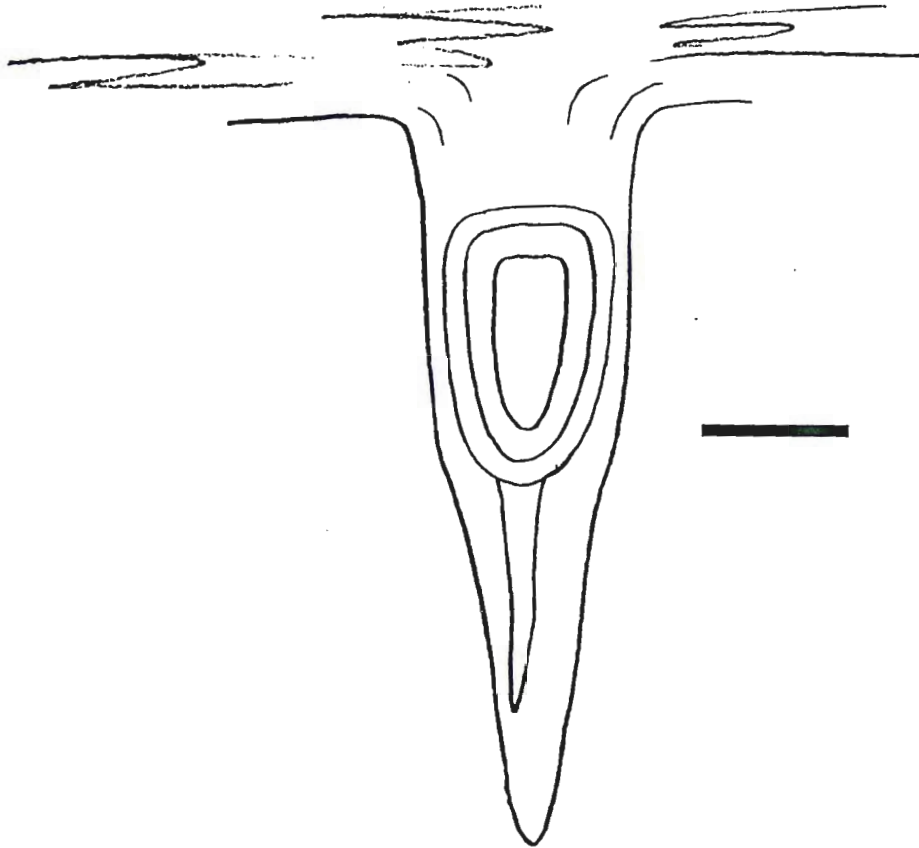


Figure 16 - Sketch of in situ Lingula and the burrow Lingulichnus. Bar scale = 1 cm



Figure 17 - Inarticulate brachiopod Lingula and burrow Lingulichnus in slabbed limestone block.

became widely distributed throughout the Hollandale Embayment. The lower Carimona Member, consists of medium thick, evenly bedded lime-mudstone and lime-wackestone with thin interbeds of shale.

Lingula has generally been thought to burrow pedicle first, however, a study by Thayer and Steele-Petrovic (1975) has indicated the opposite. They observed that the linguloid brachiopod Glottidia pyramidata uses a stiffened pedicle to prop itself up and enters the substrate anterior end first with the pedicle valve down. The valves are used in a complex series of four motions: scissoring, rotary sawing, sliding and gaping to enter the substrate, dragging the pedicle behind forming a U-shaped burrow. When the brachiopod reappears at the surface it is in the feeding position with the anterior up and the pedicle extending down into the burrow. The brachiopod's angle of penetration into the substrate determined the U's form and depth. If initial penetration was at a low angle, the resulting U was shallow and broad. If initial penetration was at a high angle, it resulted in either deep or shallow individual U's.

Owing to the evolutionary conservatism shown by lingulids, a reasonable assumption can be made that observations on living species can be extended to those of the Paleozoic (Paine, 1963, 1970). Thayer and Steele-Petrovic (1975) suggested the burrowing process responsible for the U-shaped burrow formed by Glottidia pyramidata was used by all living and fossil lingulids, and was likely an early evolutionary development permitting the successful exploitation of the infaunal habit by suspension feeders. All known occurrences

of Lingulichnus have been assigned to the species Lingulichnus verticalis, since no fossil U-shaped burrow has been reported. However, the discovery of Lingulichnus verticalis in the Lower Cambrian strata of southern Labrador by Pemberton and Kobluk (1978) would seem to confirm that burrowing was an early evolutionary development by linguloid brachiopods.

Paine (1970) noted that living lingulids are physiologically adapted to an intertidal mode of existence and that most species inhabit shallow, sandy substrates. When observed in modern silt and clay sediments, lingulids are found at depths of 10 meters or more. While recent observations have extended the depth range of Paleozoic lingulids into sediments of the outer shelf and basin environments (Pickerill, 1973; Watkins and Berry, 1977; Percival, 1978; Cherns, 1979; Pickerill, Harlan, Fillion, 1983), the predominance of reports remain from shallow marine habitats.

Thayer and Steele-Petrovic (1975) suggested that lingulids were unable to penetrate most fine-grained carbonate materials, citing Keller and Bennet (1968) who found that calcareous oozes frequently have shear-strengths 10 to 100 times greater than clay-sized non-carbonate sediments. The brachiopods observed by Thayer and Steele-Petrovic (1975), which were all greater than 1.0 cm in length, burrowed to depths ranging from near zero to 5 cm in medium-grained quartz sand. The Platteville Lingula burrows range in depth from 4.0 to 7.0 cm indicating that the ability of lingulids to burrow in fine-grained carbonates is at least comparable to their ability in medium-grained quartz sand.

Soft bottom sediments with low shear-strength are easily resuspended, producing turbid conditions which may foul the mantle organs of suspension-feeders. Resuspension can be accomplished by the intensive reworking of a mud bottom by deposit feeders since that produces a surface that is easily resuspended by low-velocity currents (Rhoads and Young, 1970). However, high shear-strength also reduces the likelihood of the sediment being resuspended (Thayer and Steele-Petrovic, 1975). High shear-strength may have compensated for the intensive bioturbation evidenced in Platteville carbonates and contributed to a satisfactory environment for lingulids.

Thalassinoides

Among the locally dominant trace fossils found in the Platteville is the ichnogenus Thalassinoides (Figure 18). Thalassinoides has been described frequently in rocks ranging in age from Mesozoic to the present. More recently the trace has been reported from rocks of Lower Paleozoic age including Ordovician, e.g. from the Great Basin of Nevada (Miller, 1977; Sheehan and Schiefelbein, 1984), Saskatchewan and Manitoba (Kendall, 1977), the Canadian Arctic (Morrow, 1978), and Wisconsin (Delgado, 1983).

Thalassinoides consists of a complex three dimensional burrow system which is a predominantly horizontal network with shafts ranging from 0.75 to 2.5 cm in diameter, sometimes swelling to 4.5 cm at turnarounds and branching points. Branches are most commonly a Y at a 20 to 30 degree angle, less



Figure 18 - Thalassinoides burrows (above card) in the Carimona Member of the Platteville, Lucky Hill road cut. The pickhead (lower left) is placed at the level of the Deicke bentonite.

frequently as T branchings at an angle of 70 to 90 degrees. The diameter of T branches maybe considerably less than the main shaft.

Thalassinoides burrows are generally attributed to the work of decapod crustaceans. Decapods had been thought to have evolved in the Jurassic, leaving the origins of Paleozoic burrows to some unknown organism (Glaessner, 1969). This assumption has been questioned since the discovery of decapods in Devonian strata (Schram, Feldmann, Copeland, 1978). The identity of the actual Ordovician burrower remains in question.

The recognition of Thalassinoides in Paleozoic strata has contributed to the controversy concerning depth of burrowing in the early Phanerozoic. Thayer (1979), Ausich and Bottjer (1982) and other writers have proposed that infaunal suspension and deposit feeding had not yet developed in the early Paleozoic. Their arguments were refuted by Miller and Byers (1984) who noted that the rock record contains many indications to the contrary. Sheehan and Schiefelbein (1984) described Ordovician Thalassinoides burrows from fine-grained carbonates of the Great Basin which extended at least 10 cm and possibly 1 to 3 meters below the sediment-water interface. Observations of burrows in the Platteville concur with those of Sheehan and Schiefelbein. The depth of Thalassinoides burrows observed in the Platteville ranges from 10 to 25 cm. Because of the difficulty in observing a large three dimensional burrow system it is possible that the burrow depth could have been considerably greater, possibly reaching the depths observed in the Great Basin strata.

Problematica type I

No trace fossil assemblage would be complete without at least one problematic burrow, and the Platteville's is no exception. While similar to several different genera, no positive identification has been made and for that reason this common Platteville trace remains unnamed. Problematica type I consists of a short horizontal cylindrical burrow always preserved in convex hyporelief (Figure 19). The burrow ranges from 3.5 to 6.0 cm in length and 3.5 to 5.0 mm in diameter. In all cases the ends of the burrow terminate abruptly and then turn up into the substrate at a very high angle. The outer edge of the up-turns is either rounded or slightly flattened.

Determination of burrow morphology was very difficult due to the lack of contrasting textures or colors in the fine-grained lime-mudstone. Slabbing parallel and perpendicular to the length of the burrow suggested that it consisted of 2 vertical shafts converging slightly towards the bottom with spreiten between them (Figure 20a). This was confirmed by X-rays of serial horizontal sections which showed that the two vertical shafts separated as they ascended with a uniformly disturbed band forming spreiten between them. The maximum height observed was approximately 5 cm, at which point the trace was totally obscured by subsequent bioturbation.

The identification of this trace was complicated by the lack of a clearly visible specimen to examine. Traces with vertical spreiten like Diplocraterion, (Figure 20b) are normally associated with higher energy conditions (Fursich,



Figure 19 - Problematika type I preserved in convex hyporelief on a float block, Nerstrand quarry.

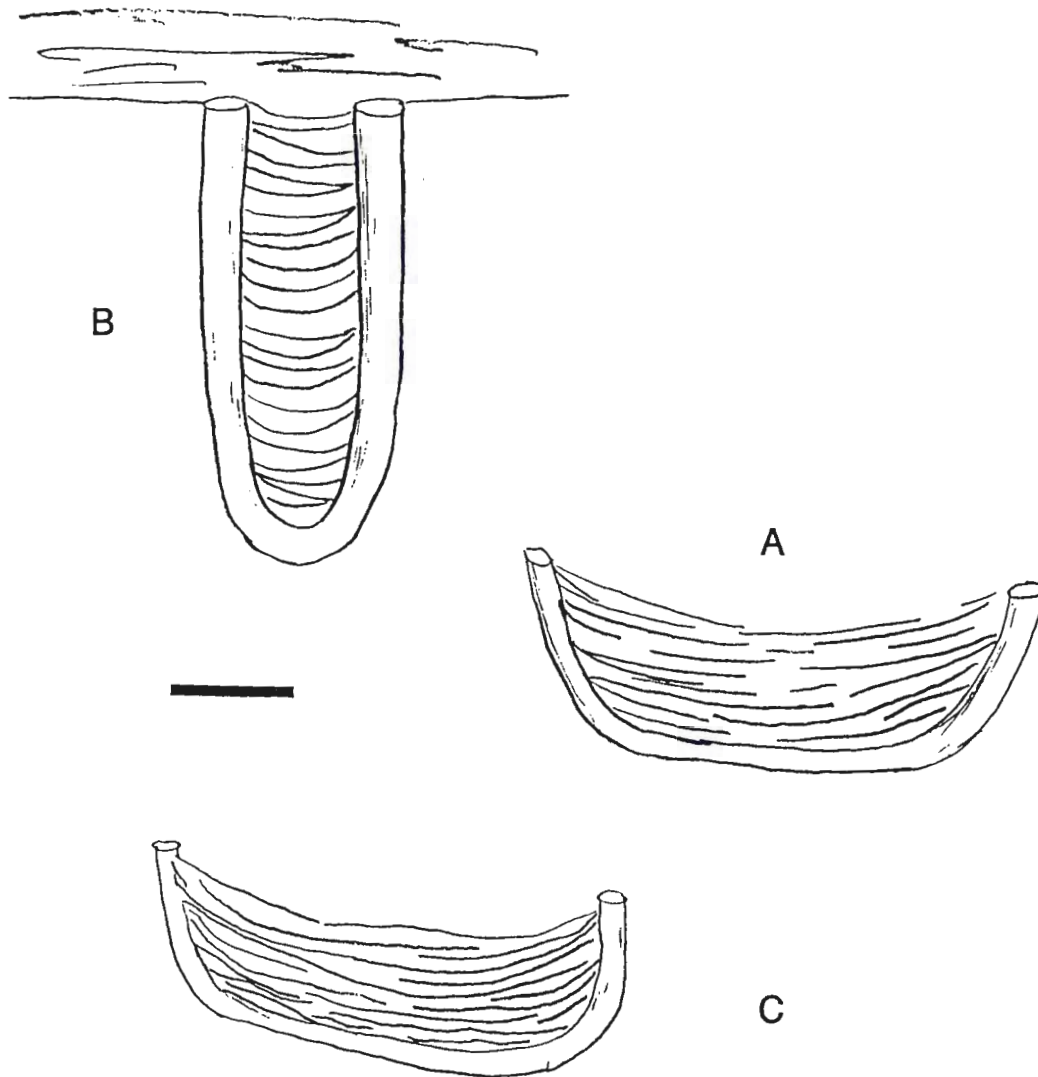


Figure 20 - (A) Problematica type I - sketch of morphology determined from slabbed limestones and X-rays. (B) Diplocraterion parallelum (C) Teichichnus rectus (based on Chamberlain, 1978). Bar scale = 1 cm

1974b, 1975; Pemberton and Frey, 1984) than those indicated by Platteville strata. One possible species would be Teichichnus rectus (Figure 20c) with which there is a distinct similarity. However, Problematica type I is uniform in size, morphology and location within the strata, features not associated with Teichichnus rectus. Teichichnus sp. is commonly found within limestone beds of the Platteville and is distinctly different from Problematica type I.

HARDGROUND BORERS AND ENCRUSTERS

"A bed of limestone is regarded as a hardground if its upper surface has been bored, corroded, or eroded (by abrasion), if encrusting or other sessile organisms are attached to the surface, or if pebbles derived from the bed occur in the overlying sediment" (Bathurst, 1975). Most commonly hardgrounds are thought of as syndepositional lithified surfaces which once formed a rigid sea floor (Palmer, 1978). Reviews of the subject may be found in Bromley (1975), Kennedy and Garrison (1975), and Bathurst (1975).

Hardgrounds are common in Middle Ordovician limestones of the Upper Mississippi River Valley. Commonly they have been referred to as "corrosion" or "discontinuity" surfaces. In the Platteville, hardgrounds are most prominent in the Pecatonica Member, especially the top where three are found in close succession. One of the most prominent hardgrounds in Ordovician strata of the Upper Mississippi River Valley occurs at the top of the Pecatonica Member. The horizon is traceable from Minneapolis, Minnesota northeast to the upper

peninsula of Michigan and south to north-central Illinois (Templeton and Willman, 1963).

The wide geographic extent of the Pecatonica hardground probably represents the greatest break in time of any of the hardgrounds that occur in the Platteville (Dathe, 1983). Estimates of the amount of time involved in cementation of a hardground vary by many orders of magnitude. Shinn (1969), using radiocarbon dating, calculated that some modern hardgrounds in the Persian Gulf began to lithify less than 1000 years ago. In contrast, Lindstrom (1963) calculated approximately 200,000 years for the lithification and burial of some Ordovician hardgrounds in Sweden. Regardless of the amount of time involved, the abundance and similarity of the trace fossil Trypanites throughout the region indicates uniform conditions during the period of nondeposition (Byers and Stasko, 1978).

Almost inevitably the hardgrounds contain Trypanites weisei, (Figure 21) a small cigar shaped boring approximately 1.0 mm in diameter and up to 2.5 cm in length, oriented about 30 degrees from vertical in the substrate. Trypanites weisei is widespread in the Middle Ordovician of the Upper Mississippi River Valley, having been described in the Platteville of southwestern Wisconsin by Stasko (1974), Byers and Stasko (1978), and Byers (1983), the Galena Group by Palmer and Palmer (1977), and Palmer (1978). While the organism responsible for the boring is unknown, the boring's morphology is similar to

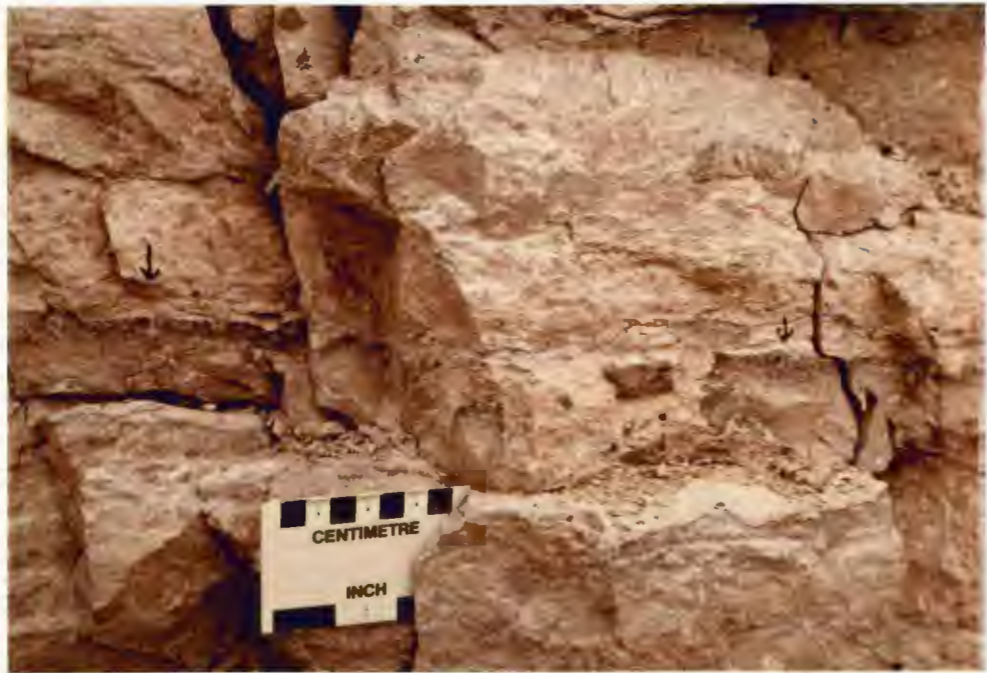


Figure 21 - Trypanites weisei (below both arrows) located in the hardground at the top of the Pecatonica Member, west Spring Grove quarry. See sketch in Appendix IV.

those created by the modern sabellid polychaete Potamilla sp. (Pemberton, Kobluk, Yeo, and Risk, 1980) and was probably created by a similar organism.

While borings are most common in hardgrounds, they are not restricted to those surfaces. The shells of cephalopods are frequently the only solid surface rising above the bottom muds. Most commonly these shells have been truncated by the action of scour and (or) dissolution, at which time the interior portions are subject to burrowing and boring (Figure 22). Where intact, the upper surface of the shell may be the site of borings.

In addition to borings, hardgrounds (or cephalopods) may be the site of attachment for encrusters which require firm or cemented substrates (Goldring and Kazmierczak, 1974). While no encrusting was observed on hardgrounds (at least on the vertical, cross-sectional faces observed), it was noted on cephalopods. Brachiopods occurred in patches or nests on several cephalopods which had projected above the sediment (Figure 23). Similar observations have been made in fine-grained lithologies and attributed to localized settling of larvae on solid objects projecting above an otherwise unstable bottom (Hallam, 1961; Ager, 1965; Rhoads, 1975; Bretsky, Bretsky and Schaefer, 1977).

DOLOMITIC MOTTLING

Dolomitic mottling is a common feature of Middle Ordovician limestones in the Upper Mississippi River Valley as well as throughout North America. The

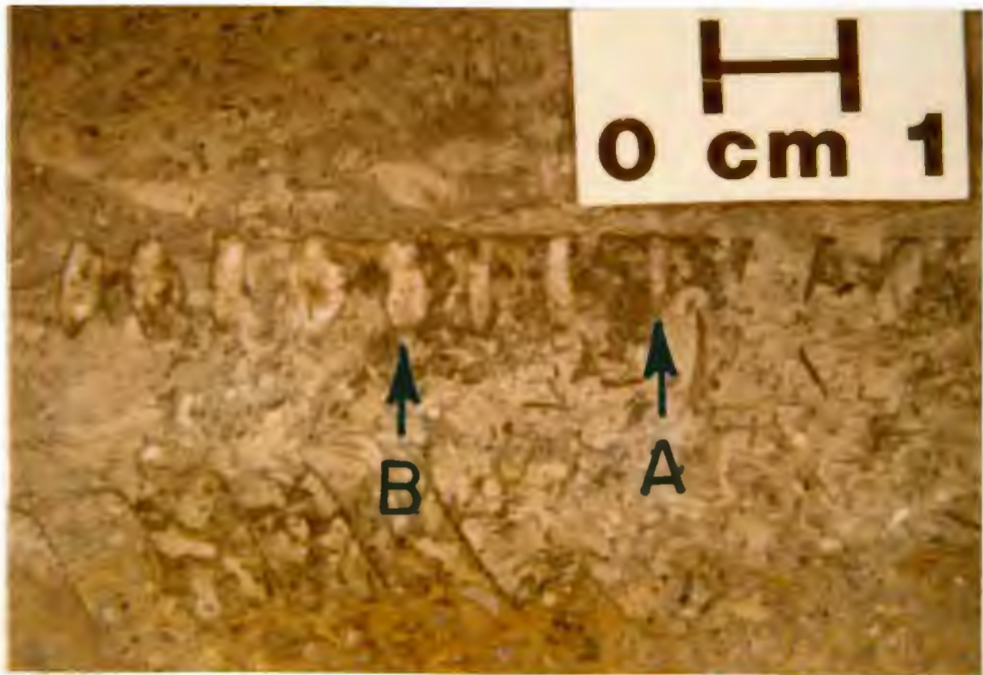


Figure 22 - Truncated shell of an Endoceras cephalopod (note septa) bored by (A) Trypanite weisei and (B) pouch-type Trypanities sp.



Figure 23 - Brachiopods nested upon an Endoceras cephalopod which had extended above the substrate surface, Carimona Member, east Spring Grove quarry.

origin of these mottled dolomitic limestones has been shown to be directly associated with burrowing prior to dolomitization (Beales, 1953; Fisher, 1970; Kendall, 1977; Morrow, 1978; Byers and Stasko, 1978).

Observations on the relationship between dolomitization and burrowing in the Platteville extends back more than 40 years. Griffin (1942) studied the dolomitic limestones of the Platteville in east-central Minnesota. He recognized that areas of dolomitization seemed to be controlled by permeability, and that permeability may have been enhanced locally by the activity of organisms. Majewske (1953) in his study of the Platteville in the region of the Twin Cities noted that dolomite was "apparently related to burrows."

More recently Dathe (1983) made a comprehensive study of the origin of mottled dolomitic limestones in the Platteville Group of northern Illinois. His research extended into southwestern Wisconsin and southeastern Minnesota including the Twin Cities Metropolitan area and is summarized below.

Mottles, defined by Dathe as "linear and irregularly subcylindrical volumes of different texture, mineral composition, coloring and weathering resistance in carbonate rocks attributed to the burrowing of sediment-eating organisms of unknown zoologic affinity." Three reasons for this conclusion were cited: 1) the mottles have cylindrical cross-sections except where flattened by compaction and may branch, 2) they abut against and follow the contour of larger fossil fragments, 3) the mottles display a constant diameter throughout the stratigraphic and geographic range of the Platteville study area. The burrows

were interpreted to be a type of Chondrites. The scenario postulated for the development of the mottled dolomitic limestones in the Platteville is summarized in Table 2.

The observations of Dathe were confirmed by staining done in the course of this study. Where dolomitization had occurred, the preferential site of dolomite was in and around burrows. However, while Chondrites burrows were dolomitic, the dolomitization was not limited to that trace. Any infaunal trace which disturbed the sediment and increased permeability appears to have been capable of enhancing dolomitization.

BENTONITE HORIZON

Bentonites are a common element of Middle Ordovician stratigraphy throughout the Upper Mississippi River Valley. They are most commonly defined as rocks "...composed almost entirely of montmorillonite and colloidal silica produced as the alteration products of volcanic debris, generally a tuff or volcanic ash...the result of either a single eruption or of several eruptions within a very brief period, perhaps a few years...they define a time line in the geologic section, or as close to an infinitely thin synchronous surface as it is possible to get in geologic materials" (Ehlers and Blatt, 1980).

Middle Ordovician bentonites differ from common montmorillonite bentonites in their high potassium content, and are frequently referred to as K-bentonites (Weaver, 1953). Mossler and Hayes (1966) found that K-bentonite

TABLE 2
Summary of the hypothesized origin of mottled dolomitic limestones
in the Platteville from Dathe (1983).

Essentially Contemporaneous:

- 1) Deposition of limestone in a shallow marine environment.
- 2) Burrowing of sediment by organism - the sediment may partially infill burrows.
- 3) Partial lithification - may modify and deform burrows.
- 4) Compaction produces fractures in the sediment.
- 5) Cracks and fractures filled with sparry calcite.

Early Diagenetic:

- 1) Dolomitization, by fluids, of the permeable burrows - may further modify burrows.
-

horizons tend to be individually thicker and more common in the direction of the Paleozoic Appalachian mobile belt, which was their probable source.

Examination of paleowind directions by which the ash would have been dispersed supports this conclusion (Figure 7).

In view of the approximately 900 miles between the Hollandale Embayment and the Appalachian mobile belt, probably only the most significant ash plumes could have been transported in sufficient volume to form a bentonite horizon. Such a horizon could have been the result of a single eruption or a series of major abrupt eruptive pulses over a brief interval of time. This would be roughly equivalent to the eruptions of Mount St. Helens during 1980 although larger in scale.

The middle Ordovician Deicke bentonite (Figure 24) was deposited in the warm shallow waters of the epeiric Platteville sea. The significance of a single eruption on benthic marine life would be dependent upon the the total volume of materials added to the water column and sea floor, while the effect of a series of eruptive pulses would depend upon their frequency as well as their volume.



Figure 24 - The Deicke bentonite (orange and white layer) above a layer of dark brown finely laminated shale, Nerstrand quarry.

BURROW DEFORMATION DUE TO COMPACTION

Bentonite Compaction

In order to understand the magnitude of the eruption, an estimate of the original thickness of the bentonite prior to compaction was made based upon burrow deformation. Burrows parallel to bedding which characteristically have a circular cross section (such as Chondrites or Planolites) become elliptical when compressed (Figure 25). If the infill is essentially the same as the surrounding sediment, then the dimension of the two axes of the ellipse can indicate the amount of compaction the sediments have undergone since the burrow was formed (Crimes, 1975b).

Measurements of the two radii of the ellipse are used to calculate decompaction using the formula

$$N_d = r_o / r_1$$

where N_d = the decompaction number, r_o = the original radius, and r_1 = the radius of the compacted burrow perpendicular to bedding (Wetzel and Aigner, 1986).

Twelve large diameter, fragmentec burrows identified as Chondrites and Planolites were observed in the bentonite at four different field locations (Table 3; Figure 26). Each of the twelve burrows displayed deformation; however, two were much less elliptical. It was assumed that these two were formed late in the compaction process and were not included in the calculation. Using these data, N_d was calculated to be equal to 3.86. An average thickness for the

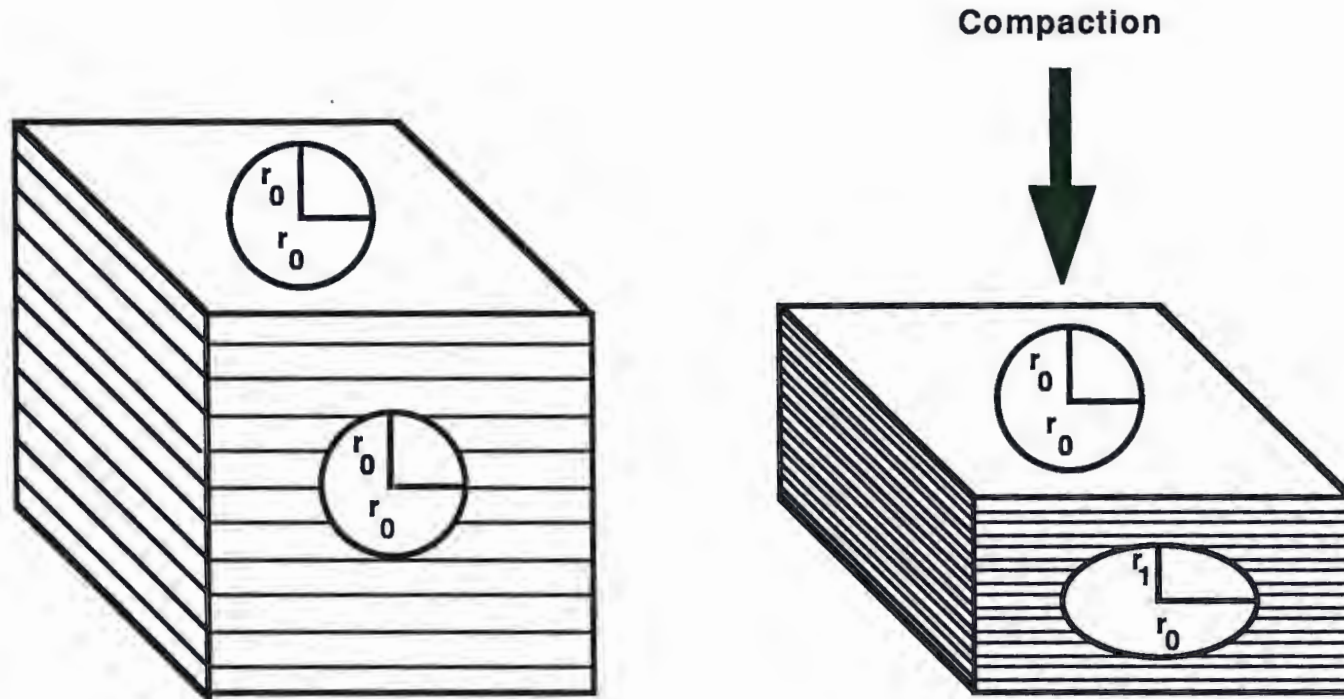


Figure 25 - Estimation of compaction of deformed burrows originally having circular cross sections. Left shows uncompact sediment while the right shows the compacted state (modified from Wetzel and Aigner, 1986).

TABLE 3
 Ellipse measurements of burrows in the Deicke bentonite.

No.	Location	r_o	(Both in mm)	r_1
1	North Douglas Quarry	4.5		1.0
2	North Douglas Quarry	3.0		0.75
3	North Douglas Quarry	4.5		1.0
4	East Chatfield Quarry	2.5		0.75
5	East Chatfield Quarry	4.75		1.0
6	East Chatfield Quarry	5.25		1.5
7	East Chatfield Quarry	3.5	Not Used	2.5
8	East Spring Grove Quarry	4.25		1.25
9	East Spring Grove Quarry	3.5	Not Used	2.5
10	Sogn Road Cut	1.5		0.375
11	Sogn Road Cut	3.0		1.0
12	Sogn Road Cut	3.0		0.75
		Sums:	36.25	9.375
			-----	-----
		Averages (N = 10):	3.63	0.94

$$N_d = r_o / r_1 = 3.63 / 0.94 = 3.86$$

$$N_d \times \text{Thickness} = 3.86 \times 7.0 \text{ CM} = 27.03 = 27.0 \text{ CM}$$



Figure 26 - One of twelve large diameter fragmented burrows found in the Deicke bentonite.

bentonite was calculated based on measurements taken by Majewske (1953), Ford (1958) and Hoefft (1959) at 24 different locations; this average was 7.0 cm. Using the formula, the calculated thickness of the wet, noncompacted bentonite was 27.0 cm. This should probably be viewed as a minimum figure, since some compression must have occurred prior to the repopulation of the region and burrowing into the bentonite.

Shale Compaction

Compressed burrows are also found in shale interbeds. Using calculations described for the burrows in the bentonite horizon, the shale interbeds were originally 3 to 5 times their present thickness.

NON-BIOTURBATED VS WELL-BIOTURBATED

Non-bioturbated sediments accumulate when the rate of deposition exceeds the ability of the benthic organisms to turn the sediments over. The resulting accumulation of sediments thereby retains the original depositional texture. For well-bioturbated sediments the opposite is true, while in between is a complete bioturbation/textural gradient. Any environmental change which effectively decreases the ability of organisms to turn the sediment over will be reflected in a non-bioturbated depositional texture. Increased deposition, influx killings associated with increased turbidity or changes in salinity are among the most common environmental changes that can effect the depositional texture.

Bioturbation Pattern in Limestone

Repeated reworking resulting in a totally bioturbated limestone is the most common pattern observed in the Platteville. In that instance the lower portions of deep pre-existing burrows are the only parts to escape destruction by subsequent bioturbation, which usually affects only the upper few centimeters. In other instances, horizons of locally intense bioturbation were wholly preserved and may represent local breaks in deposition with continued bioturbation. The overall pattern matches those described by Goldring (1964), Howard (1975, 1978), and Ekdale et al. (1984) as one of slow continuous deposition or slow discontinuous deposition without significant erosion (Figure 27).

Bioturbation Pattern in Shale

Shale interbeds are numerous in the Platteville and are especially prominent in the Carimona Member. The majority of shale interbeds are well-bioturbated (non-laminated/fissile) while a significant minority are non-bioturbated and display the original laminations characteristic of fine-grained particles deposited in calm water. Commonly the non-bioturbated beds extend to adjacent outcrops, while a few remain non-bioturbated throughout the Hollandale Embayment. The most notable is the distinctly and pervasively laminated shale interbed directly beneath the isochronous Deicke bentonite. This interbed ranges in thickness from 2.0 to 6.0 cm and is found in



Figure 27 - Appearance of a freshly exposed, totally bioturbated limestone bed just above the Deicke bentonite, east Spring Grove quarry.

almost every outcrop in which the bentonite is exposed in southeastern Minnesota.

Laminated shale interbeds are attributed to the rapid deposition of terrigenous sediments and were probably associated with more turbid conditions. The extensive laminated shale beneath the Deicke bentonite probably represents similar conditions which were compounded by the high mortality of the benthic fauna and subsequent lack of bioturbation resulting from the ash fall.

OXYGEN

Aerobic organisms vary in their oxygen requirements. In most well-oxygenated marine environments the fauna would be shelly, diverse and abundant, while in an absolutely anaerobic environment no animal life would be present. Between these extremes a decrease in oxygen is reflected by a community of lower diversity and abundance which uses the available oxygen for respiration rather than the formation of hard parts (Rhoads and Morse, 1971). Subjective observations indicated that shells were less common in the thick shales than in the carbonate sequences of the Platteville, however, this maybe the result of turbidity.

The diversity of trace fossils is known to decrease in tiers as the bottom water becomes increasingly anoxic (Figure 28). Chondrites is typically the last trace fossil present (Bromley and Ekdale, 1984; Ekdale et al., 1984).

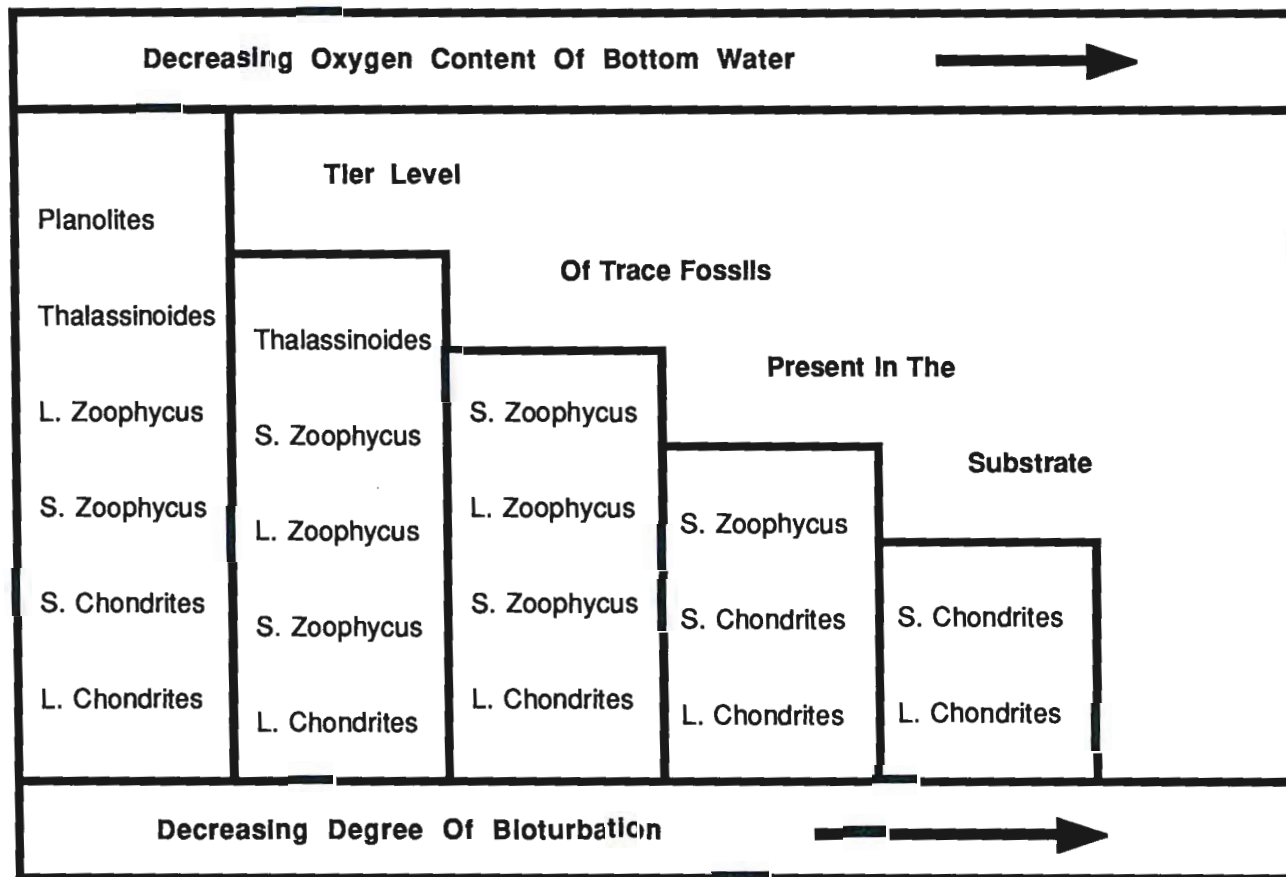


Figure 28 - Trace fossil tiers as the oxygen content of the bottom water decreases (modified from Bromley and Ekdale, 1984; Ekdale et al., 1984).

The organisms responsible for Chondrites probably preferred oxygen-poor interstitial environments (Ekdale, 1985). If Figure 28 were projected one tier further, the small form of Chondrites would be the only trace fossil present before the onset of totally anoxic conditions. Physiologically that is sound since small organisms require less oxygen than large organisms.

When Platteville shales are laminated, they are found to contain only Chondrites burrows. The smaller species which probably could not have extended more than 3 to 5 cm below the sediment surface (Bromley and Ekdale, 1984) is far more common than the larger species (Figure 29). The organisms responsible for Chondrites may have tolerated the influx of terrigenous sediments better or have repopulated the region faster than the rest of the benthic population. However, the organism's probable preference for oxygen-poor interstitial environments cannot be discounted.

Similarly, Chondrites' preference for an oxygen-poor interstitial environment suggests that such conditions existed within the mudstones and fine-grained wackestones of the Platteville Formation, as well as within the shales. Large Chondrites, capable of burrowing up to a meter into the sediment (Bromley and Ekdale, 1984) was probably responsible for most deep reworking of the Platteville, where it occurs in some fine-grained limestone horizons to the exclusion of all other traces. This is probably related to the fact that as grain size decreases, so do the effective porosity and permeability of the sediment, resulting in poor interstitial circulation, the buildup of waste products and



Figure 29 - Compressed small Chondrites (below the card) in the shale interbed 45 cm below the Deicke bentonite, Nerstrand quarry.

the depletion of free oxygen (Purdy, 1964; Longbottom, 1970; Rhoads and Young, 1970).

STORM

The Platteville Formation contains horizons of packstone in sharp contact above and below with wackestone. Infrequently the clasts within the packstones display abrasion and breakage, indications of physical reworking by wave or current-generated turbulence. Physical reworking of the bottom results in a pattern of burrow truncation and alternating bioturbation textures (Howard and Frey, 1983; Pemberton and Frey, 1984). The pattern typically consists of an intact bioturbated layer truncated by a coarser basal deposit (if coarser material is present) grading into finer sediments. In both the coarse and fine reworked sediments, previously existing burrows are destroyed. No such patterns were observed and if they had formed in the Platteville strata associated with the packstone layers, secondary bioturbation destroyed it.

WAVY BEDDING

The wavy bedding of the McGregor Member has been ascribed to wave and current ripple marks by Jacka (1957), Asquith (1963), and Sloan (1972). It was noted that within the shale partings separating limestone beds were flattened, ribbon-like Chondrites burrows which followed the irregular contours but never penetrated the ripple-like waves or nodules. Furthermore, the

burrows were most compressed at the apices of the structures where the shale partings were subject to the most compression. Identical observations have been reported (Stasko, 1974; Byers and Stasko, 1978) on burrows within the wavy bedding of the McGregor Member in southern Wisconsin. The flattening of originally circular burrows around wavy bedding structures was attributed to diagenetic differential compaction of a homogeneous bioturbated sediment. On modern seafloors where wave ripples form, similar types of (circular) burrows are often so "cemented" by organic secretions that they resist breakup. The burrows, when exhumed by wave action may litter the ocean floor (Darby, personal communication). That the maximum compression of both the burrows and shale coincided with the nodule's apices is alone insufficient evidence for a diagenetic origin. However, together with the non-penetration of any nodule by a burrow strongly suggests a diagenetic origin.

CEPHALOPOD ORIENTATION

Early in the field season it was noted that a large number of orthoconic cephalopods of the genus Endoceras were present in the Platteville. The shells of these cephalopods are streamlined like ice cream cones. After death, it seems likely that the cephalopod shell should come to rest in a preferred current-orientation; the long axis should parallel current flow. Physical structures which might alter the preferred current-orientation such as troughs in a wave-ripple zone were not observed.

A total of 28 Endoceras shells were observed, of which 2 each were in the Pecatonica and McGregor Members, while 24 were in the Carimona Member (Figure 30). Of the latter, 17 were in the bentonite horizon or the limestone beds bounding it. The distribution and orientation of those shells are shown in Table 4. When plotted on a rose diagram (Figure 31), the orientation of the cephalopods shows strong bimodal-bipolar distribution northwest-southeast. This northwest-southeast distribution would be compatible with current-driven sediment influx from the Transcontinental Arch to the northwest. The data also agree with Bretsky et al. (1977) who suggested that sediments were washed from west to east in southeastern Minnesota and southern Wisconsin during the period of Platteville deposition.

SUMMARY

After completion of this investigation of trace fossils in the Platteville Formation the following general conclusions were reached:

- 1) The Platteville ichnoassemblage is typical of the Cruziana ichnofacies, possessing a relatively high population density and diversity and dominated by infaunal deposit and suspension feeders.



Figure 30 - Cephalopod immediately above the card which is placed in the weathered out bentonite horizon.

TABLE 4
Cephalopod distribution and orientation within the Platteville Formation

NO.	BEARING	LEVEL	OUTCROP
1.	300	2 m below Deicke Bentonite [mid-McGregor]	Lower Nerstrand road cut
2.	305	1.1 m below Deicke Bentonite [basal Deicke]	Lower Nerstrand road cut
3.	120	Basal Pecatonica-just above Glenwood	South Fountain road cut
4.	120	Basal Pecatonica-just above Glenwood	South Fountain road cut
5.	010	On Deicke Bentonite	Lucky Hill road cut
6.	328	On Deicke Bentonite / 9 m west of #6	Lucky Hill road cut
7.	062	Deicke-McGregor contact, 15 cm below Deicke Bentonite	Lucky Hill road cut
8.	140	Deicke-McGregor contact	North Douglas Quarry
9.	110/290	2 Beds [30 cm] above top of Deicke Bentonite	North Douglas Quarry
10.	120/300	1 Bed [2 m] above top of Deicke Bentonite	North Douglas Quarry
11.	040/220	1 Bed [2 m] below Deicke Bentonite	North Douglas Quarry
12.	075/255	2 Beds [30 cm] below Deicke Bentonite	North Douglas Quarry
13.	140	2 Beds [30 cm] below Deicke Bentonite	North Douglas Quarry
14.	300	Upper McGregor	Wanamingo Quarry
15.	145	Lower Deicke 30 cm above bentonite	North Pine Island Quarry
16.	140	Top of Deicke Bentonite	North Pine Island Quarry
17.	100	20 cm Above top of Deicke Bentonite & #16	North Pine Island Quarry
18.	070/250	Top of Deicke Bentonite	North Pine Island Quarry
19.	130/310	Top of Deicke Bentonite [?]	North Pine Island Quarry
20.	100	Top of Deicke Bentonite	Danesville Quarry
21.	240	15 cm Above top of Deicke Bentonite	Golden Hill road cut
22.	122	Top of Deicke Bentonite	East Chatfield Quarry
23.	125/305	2 m Above top of Deicke Bentonite	East Chatfield Quarry
24.	335	Top of Deicke Bentonite	West Spring Grove Quarry
25.	300	Below Deicke Bentonite	West Spring Grove Quarry
26.	120	Top of Deicke Bentonite	West Spring Grove Quarry
27.	120	Top of Deicke Bentonite	Wangs Quarry
28.	070	10 cm Below Deicke Bentonite	Saratoga road cut

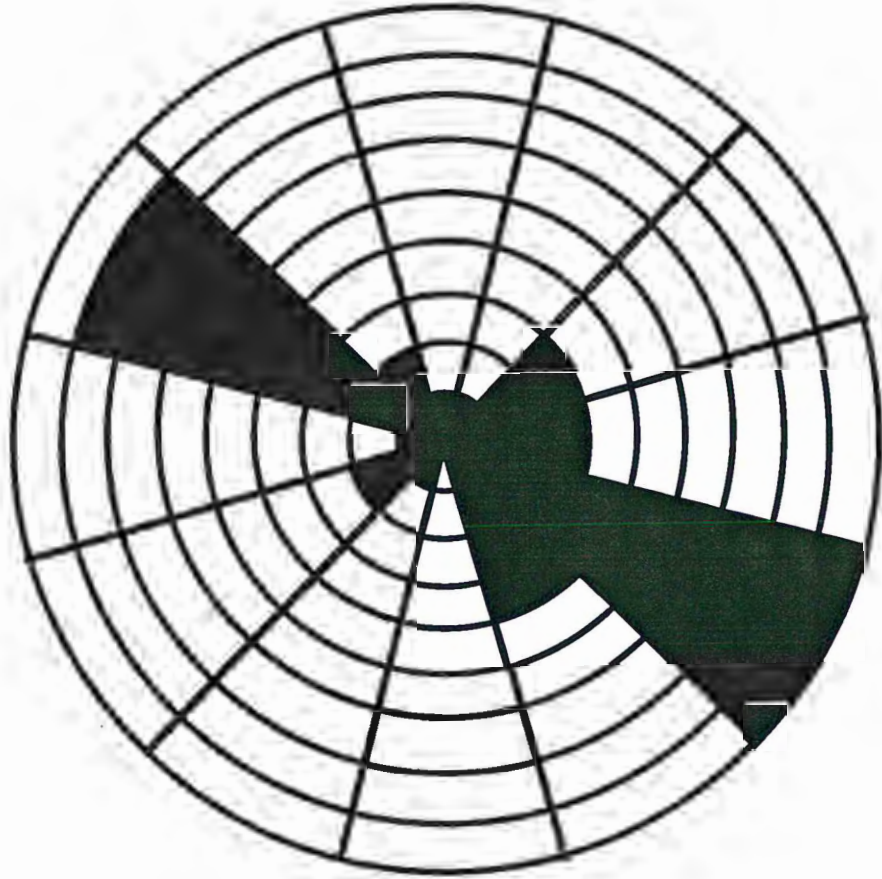


Figure 31 - Paleocurrent data from the orientation of cephalopod shells in the Platteville. Each ring equals one reading. (N = 28)

- 2) The dominant association consists of Planolites and both large and small forms of Chondrites. These three traces are unrestricted geographically throughout the area, although Chondrites may occur to the exclusion of all other traces including Planolites at some horizons.

- 3) The ichnogenera Bifungites and Lingulichnus are restricted to, and relatively common in the Carimona Member including the bentonite horizon. Bifungites is associated exclusively with shallow marine environments from shallow nearshore to deep basin but finds optimum conditions (modern Lingula) in the shallow marine environment. Despite the lack of preserved physical sedimentary structures, water depth within the Hollandale Embayment is believed to have been shallow. Estimates range from 10 to 20 meters, with near uniform conditions throughout the region.

- 4) The limestone beds bounding the Deicke bentonite enclose an essentially isochronous horizon. In addition to Chondrites and Planolites these beds contain five traces common enough to be significant: Arenicolites, Bifungites, Lingulichnus, Thalassinoides, and Problematica type I.

- 5) The 7.0 cm thick Deicke bentonite contains compressed burrows which originally had circular cross sections. Using deformation of the burrows, the original thickness of the wet uncompressed bentonite was calculated to be 27.0 cm. The same methods were applied to compressed burrows in laminated shale horizons which indicated that the shales were originally 3 to 5 times their present thickness.

- 6) Periodically terrigenous sediments flooded the Hollandale Embayment forming laminated shale interbeds among the carbonate beds. Generally, bioturbation exceeded sedimentation, resulting in a thoroughly reworked fissile shale. When sedimentation exceeded bioturbation, the shales remained laminated. Rapid accumulation of sediments may have had detrimental effects on some members of the benthic community. The only trace fossil found in laminated shale horizons is Chondrites. This exclusion of other traces is most likely related to Chondrite's tolerance of low interstitial oxygen levels and reflects those conditions within the shales.

- 7) Current direction obtained from cephalopod shell orientation indicates that sediments were transported from the Transcontinental Arch southeast into the embayment.

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APPENDIX I

SYSTEMATIC ICHNOLOGY

The following section is concerned with the description and classification of those ichnofossils found within the Platteville Formation.

The identification of different traces was accomplished with the use of the references listed at the top of each description. These references are also credited with the information under Diagnosis, Remarks, and Range.

Figure numbers given as a numeral alone refer to figures in the body of the thesis. Figure numbers given as a numeral preceded by the letter "A" refer to figures shown in this appendix.

Ichnogenus Arenicolites Salter, 1857

Hantzschel 1975, pp.W38,40, figures 24-2a,b; Chamberlain 1978, pp.27, figure 2-1; Kamola 1984, pp.531 to 532, figure 7.

Diagnosis: Consists a simple of U-shaped burrow tubes without spreiten, orientated perpendicular to the bedding. Considerable variance is seen in tube size, diameter, distance between limbs and depth of the burrow.

Classification: Dwelling burrow.

Remarks: Widely distributed, believed to be made by a marine worm or wormlike organism.

Range: Cambrian to Cretaceous.

Arenicolites sp.

Figure A1

Description: Consists of a simple U-shaped burrow without spreiten essentially perpendicular to bedding. The diameter of the burrow is 0.2 to 0.4 cm, the distance between limbs is 1.0 to 1.5 cm while the height is variable. In a few instances paired circular entrances were noted on bedding plane surfaces.

Remarks and occurrence: Arenicolites is widely distributed throughout the Platteville.

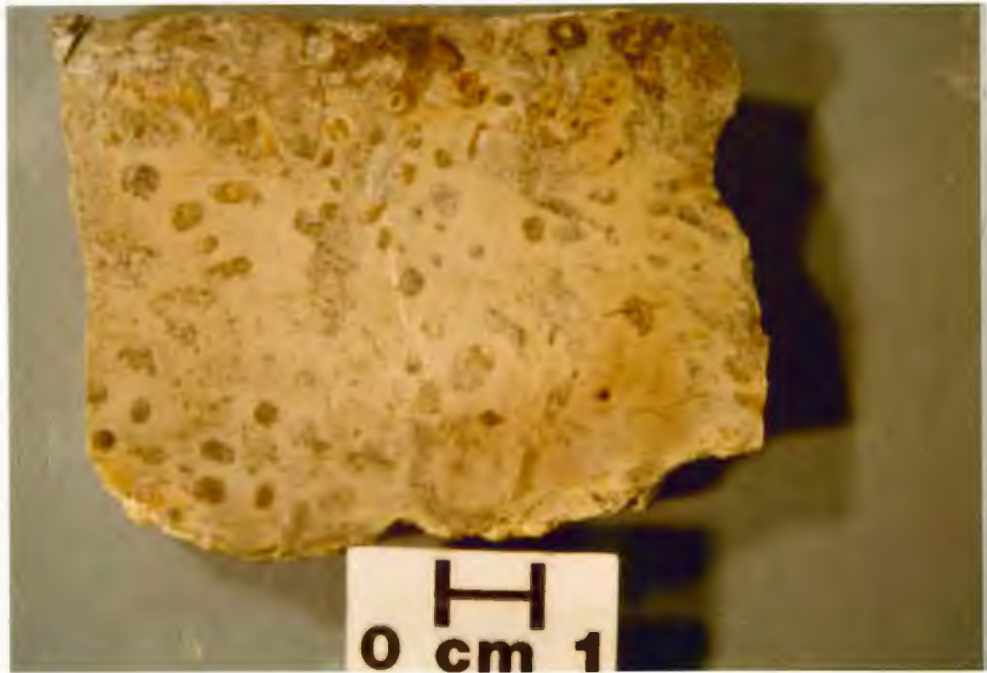


Figure A1 - Arenicolites sp. U-shaped burrow above the cm scale.

Ichnogenus Bifungites Desio, 1940

Rodriguez and Gutschick 1975, pp.18 to 34; Gutschick and Lamborn 1975, pp.193 to 212, plate 1 figure 18; Hantzschel 1975, pp.W46 to 47, figure 29-1; Pickerill and Forbes 1977, pp.87 to 92, figures 4a-i; Pickerill and Forbes 1979, pp.2026 to 2027, figures 3a,b,4b; Turner and Benton 1983, pp.452 to 453, figure 4B.

Diagnosis: Consists of a dumbbell shaped structure which is commonly 2 to 5 cm in length. Both ends are either hemispherical or arrowhead shaped chambers roughly 2X the diameter of the connecting tube between them.

Classification: Dwelling burrow.

Remarks: Believed to be the lower most protrusions of a vertical U-shaped burrow system with a chamber at the base of each vertical shaft.
Typically found in a shallow subtidal environment.

Bifungites sp.

Figure A2

Description: Dumbbell shaped burrows preserved in convex hyporelief which consist of a 0.5 cm diameter central tube joining two roughly spherical chambers 1.0 cm in diameter while the total length of the trace is 4.0 cm.

Remarks and occurrence: Five specimens were observed at different field sites. At both the north Douglas and east Spring Grove quarries



Figure A2 - Bifungites sp. Note the "dumbbell" shape.

Bifungites was noted in situ directly above the Deicke bentonite. In the east Chatfield, east Spring Grove and north Mabel quarries Bifungites was noted in float that came from the Carimona Member.

Ichnogenus Chondrites von Sternberg, 1833

Simpson 1957, pp.475 to 499, plates XXI, XXII, XXIII XXIV; Hantzschel 1975, pp.W49 to 52, figures 32 1a-f.

Diagnosis: A smooth walled, regular though asymmetrical dendritic burrow system. Interpenetration and interconnection between different burrows is not normally seen. The diameter of the burrows within a particular system remains essentially constant.

Classification: Feeding and (?)dwelling burrow system.

Remarks: The separation of Chondrites into different types is based on the relative diameter of burrows.

Range: Cambrian to Tertiary.

Chondrites type I

Figures 29, A3

Description: As per diagnosis, burrow diameter ranges from 1.0 to 3.0 mm being constant in any specific burrow system.

Remarks and occurrence: Ubiquitous throughout the Platteville at all locations.

In laminated shales small Chondrites may be the only burrow present.



Figure A3 - Chondrites type I

Chondrites type II

Figure A4

Description: As per diagnosis, burrow diameter ranges from 4.0 to 6.0 mm
being constant in any specific burrow system.

Remarks and occurrence: Ubiquitous throughout the Platteville at all locations.



Figure A4 - Chondrites type II

Ichnogenus Conostichus Lesquereux, 1876

Branson 1959, pp.82 to 82, 1960, pp.195 to 207, 1961, pp.130 to 138;

Chamberlain 1971, pp.220 to 223, figures 4:a-d plate 30:1-5; Pfefferkorn 1971,

pp.888 to 893, figures 1-5; Hofman 1979, pp.41 to 42, 44, plate 14.

Diagnosis: A wide range of biogenic structures ranging from wide cones with slightly sloping sides to forms with flat apices and nearly parallel sides. May display duodecimal symmetry with transverse constriction and longitudinal ridges and furrows on the sides. Width ranges from 3.0 to 7.5 cm and height from 4.0 to 8.0 cm.

Classification: Feeding and dwelling burrow.

Remarks: Believed to be created by burrowing anemones.

Range: Ordovician to recent.

Conostichus sp. type I

Figure A5

Description: Conical burrow tapering from 5.0 cm at the top to 2.3 cm at the base with a height of 6.2 cm. The burrow walls are regular, distinct and (?)lined. The infill is distinct from the surrounding sediment with a far higher percentage of coarse grained particles which show evidence of packing in a darker matrix.

Remarks and occurrence: Two examples of this burrow type were noted at the same level 45 cm below the Deicke bentonite and some 15 meters apart



Figure A5 - Conostichus sp. type I

at the Nerstrand Quarry. Two others were noted in the sandy basal unit of the Pecatonica Member the at south Fountain road cut.

(?)Conostichus sp. type II

Figure A6

Description: Circular burrow 2.2 cm in diameter terminating in a rounded, not pointed lower end. Oriented perpendicular to bedding with a height of 5.0 cm, originally must have extended further. Walls are unlined and somewhat irregular due to the effects of subsequent Chondrites burrowing. The burrow is filled with debris, including crinoid fragments, which is texturally different from the surrounding sediments.

Remarks and occurrence: The lower 1.0 cm of the sample consists of finely laminated shale mottled by Chondrites type burrows. Compression of the shale is evidenced by the flattening of the burrows parallel to the laminations. Chondrites burrowing occurred over a period of time as compression continued. This is evidenced by nearly flat burrows which had undergone compression for a long period ranging to nearly circular burrows which had undergone very little compression. Subsequent burrowing responsible for the large vertical burrow resulted in the deformation of shale laminae and Chondrites burrows about the rounded lower end of the burrow. A single specimen was obtained from the second limestone bed below the Deicke bentonite at Nerstrand Quarry.



Figure A6 - (?)Conostichus sp. type II

Ichnogenus Cylindrichnus Howard, 1966

Archer 1984, pp.287 to 289, figure 3-g; Hantzschel 1975, pp.W57, figure 36-4a,b.

Diagnosis: Generally tubular, straight to slightly curved burrow with a circular to oval cross section from 1.0 to 2.0 cm in diameter. Orientation ranges from horizontal to more commonly vertical.

Classification: Dwelling (domichnia) burrow.

Remarks: Found in a range of facies.

Range: Ordovician to Cretaceous.

Cylindrichnus sp.

Figure A7

Description: Per diagnosis, oriented essentially vertical. Preserved in hyporelief usually extending 0 to 1.5 cm below the overlying bed.

Remarks and occurrence: Common at several locations in the Platteville but restricted to the Carimona Member.



Figure A7 - (A) Cylindrichnus sp. (B) Gyrolithes polonicus

Ichnogenus Diplichnites Dawson, 1873

Osgood 1970, pp.365 to 367; Savage 1971, pp.222 to 225, figure 5a-d,9a-d;

Hantzschel 1975, pp.61 to 63, figure 39-4a,b.

Diagnosis: A simple 1.0 to 2.0 cm wide track consisting of 2 parallel series of grooves (epirelief) with the separate grooves radiating out from the direction of motion obliquely.

Classification: Locomotion trail.

Remarks: Considered to be the locomotion traces of trilobites. There will be considerable variation among the traces.

Range: Precambrian to Permian.

Diplichnites sp. type I

Figures 11, A8

Description: "Feather like" imprint (epirelief) with a length of 5.5 cm and a maximum width of 0.7 cm. Consists of a series of very fine linear imprints (0.1 mm by 7.0 mm) that display withdrawal markings medially. These linear imprints radiate out at an acute angle along the length of the structure. Each series consists of 7 linear imprints, incompletely paired on the opposite side. The set width is 0.5 cm while the set length is 1.2 cm. At the distal end are 4 linear imprints parallel to both each other and the length of the trace. The appearance is most similar to the way in which



Figure A8 - (A) Diplichnites sp. type I (B) Problematica type III

the barbs of a feather extend from the shaft. Hundreds of very fine circular impressions (0.25 to 0.5 mm in diameter) dot the surface alongside the scratches.

Remarks and occurrence: The trace appears to belong to a small trilobite which settled on the surface and traversed a short distance, pausing at intervals and then launched itself up into the water once again. A single specimen was obtained from the Platteville-Decorah contact at White Rock road cut.

Diplichnites sp. type II

Figures 11, A9

Description: A series of circular impressions (0.25 to 1.5 mm in diameter) across bedding surfaces. An accurate description of the series and set width was not possible because of a number of tracks and other traces.

Remarks and occurrence: Found in association with Torrowangea, in some places imprinted upon that trace. Observed at the White rock road cut at the Platteville-Decorah contact.



Figure A9 - (A) Diplichnites sp. type II (B) (?)Torrowangea sp. (C) Problematica type II

Ichnogenus Diplocraterion Torell, 1870

Hantzschel 1975, pp.w59 & 62, figures 37-2a,b; Fursich 1974b, pp.952 to 962, figures 2,5; Chamberlain 1978, pp.152 to 153, figures 93-96.

Diagnosis: U-shaped burrows with spreiten which are always perpendicular to the bedding plane. The limbs of the tubes are parallel and end in either large funnels, small shallow funnels or remain subcylindrical at the surface.

Classification: Dwelling burrow.

Remarks: Associated with the Skolithos ichnofacies.

Range: Cambrian to Tertiary.

Diplocraterion sp.

Figure 2

Description: U-shaped essentially vertical burrows which have spreiten. The main tubes have a diameter of 0.3 to 0.75 cm and a distance between vertical shafts of 2.0 to 5.0 cms.

Remarks and occurrence: Found within the St. Peter Formation.

Ichnogenus Fustiglyphus Vyalov, 1971

Hantzschel 1975, pp.W64 to 65, figure 39-2; Osgood 1970, pp.369 to 371, 432 to 433, plate 78 figures 4-9.

Diagnosis: A tunnel or trail interrupted by swellings or nodes with considerable variance in length and size. Preserved as either convex hyporelief or concave epirelief.

Classification: Crawling, feeding or dwelling trace.

Remarks: Possibly created by gastropods.

Range: Middle Ordovician to Eocene.

Fustiglyphus sp.

Figure A10

Description: Consists of a gentle curving tube parallel to bedding 1.0 cm in diameter and 31.5 cm in length which is interrupted at intervals of 2.5 to 4.0 cm by swellings 2.0 cm in diameter.

Remarks and occurrence: Four specimens were noted on the underside of a large float block from the Carimona Member at the east Chatfield Quarry.



Figure A10 - Fustiglyphus sp.

Ichnogenus Gyrolithes De Saporta, 1884

Hantzschel 1975, pp.W65,W67, figures 41-4a,b; Crimes and Anderson 1985, pp.318,321, figures 6-7,8.

Diagnosis: A vertical coiled (dextrally or sinistrally) burrow consisting of whorls essentially uniform in diameter that may branch at the upper end and reach several decimeters in length.

Classification: (?)

Remarks: All but Cambrian forms are thought to be made by decapod crustaceans.

Range: Cambrian to Tertiary.

Gyrolithes polonicus

Figure A7

Description: Consists of one-half to three-quarters of a complete whorl the diameter of which ranges from 4.0 to 5.0 cm while the diameter of an individual burrow tube ranges from 1.0 to 1.5 cm. Preserved as convex hyporelief with greater relief distal from the point where the burrow corkscrews out of the base of the bedding unit.

Remarks and occurrence: Seven specimens were observed, one in the north Pine Island quarry 30 cm above the Deicke bentonite; the others in the east Chatfield quarry on the base of large float blocks from the Carimona Member one of which was from above the Deicke bentonite.

Ichnogenus Lingulichnus Hakes 1976

(syn. Lingulichnites Szmuc, Osgood, and Meink 1976)

Hakes 1976, pp.28, figure 10, plate 6 figure 5, plate 7 figure 1a-e; Szmuc, Osgood, and Meink 1976, pp.163 to 167, figures 1,2a,b,3; Pemberton and Risk 1982, pp.100, figure 9.

Diagnosis: Tongue to spade-shaped vertical burrows with the widest dimension at the top. The aperture and upper tongue-like part appear very elliptical in transverse section. A basal stem substantially smaller in diameter having a circular cross-section may be present.

Classification: Dwelling structure.

Remarks: U-shaped structure not observed, probably due to destruction by sediment reworking.

Range: Cambrian to Recent.

Lingulichnus verticalis

Figures 15, 16, 17

Description: Per diagnosis, the burrowing depths reach 7.0 cm with up to 4.0 cm between limbs.

Remarks and occurrence: Restricted to the Carimona Member and is widely distributed.

Ichnogenus Muensteria von Sternberg, 1833

Hantzschel 1975, pp.W84; Howard and Frey 1984, pp.200 to 201 figure 1;

Pemberton and Frey 1984, pp.291, figure 5b.

Diagnosis: A distinctly walled, unlined, slightly sinuous to straight burrow with a prominent meniscate backfill, generally oriented horizontal or at a low angle to bedding.

Classification: Feeding burrow.

Remarks: Specimens have been found containing the trace making organism.

Range: Ordovician to Cretaceous.

Muensteria sp.

Figure A11

Description: A walled, unlined burrow 0.5 cm in diameter, with distinct meniscate concavo-convex segments 2.0 to 4.0 mm wide. The filling is indistinguishable from the matrix.

Remarks and occurrence: A single specimen was obtained from the Carimona Member of the Platteville at the Nerstrand quarry.

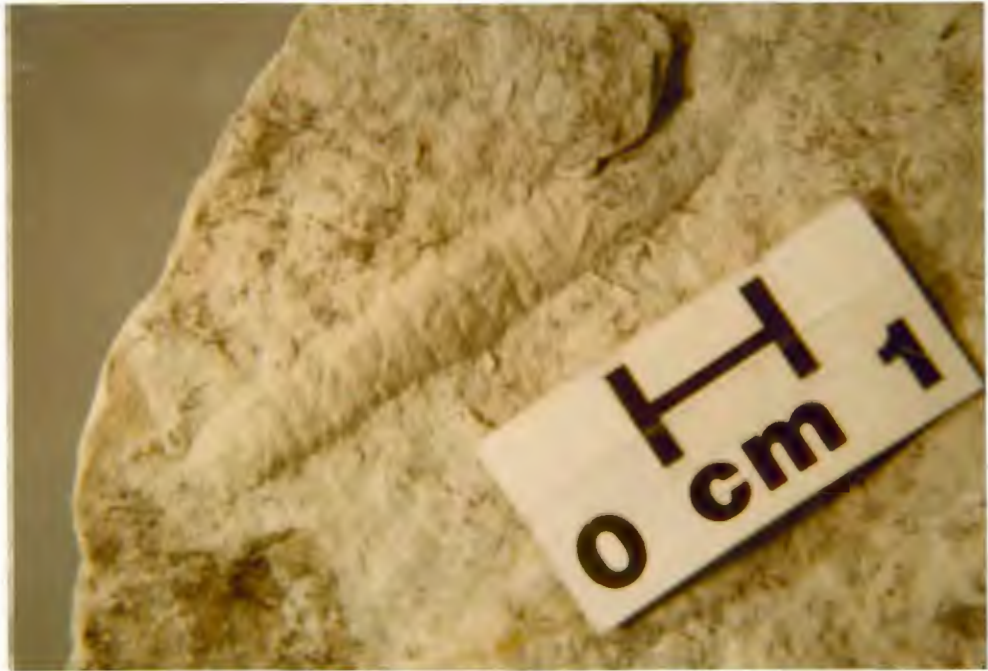


Figure A11 - Muensteria sp.

Ichnogenus Nereites MacLeay, 1839

Hantzschel 1975, pp.W83 to 84. figure 52-1c; Crimes and Germs 1982, pp.898 to 901, plate 2 figure 8.

Diagnosis: A meandering trail consisting of a central furrow (epi-hyporelief) flanked bilaterally by lobes which are leaf, ovate, or pinnate in shape. The width and size of both the furrows and lobes are variable. The meanders frequently occur in great density.

Classification: Meandering grazing trail.

Remarks: Common in the outer shelf environment.

Range: Precambrian to Recent.

Nereites sp.

Figure A12

Description: Slightly undulating furrow 9.0 cm in length, 0.3 cm wide flanked by nominal lobe-ridges.

Remarks and occurrence: A single specimen was obtained from the shale interbed located at the contact between the Carimona Member of the Platteville Formation and the overlying Decorah Formation. The trail is in lime mud immediately over and amid a coquina layer composed of articulate brachiopods valves which are avoided by the meanders.

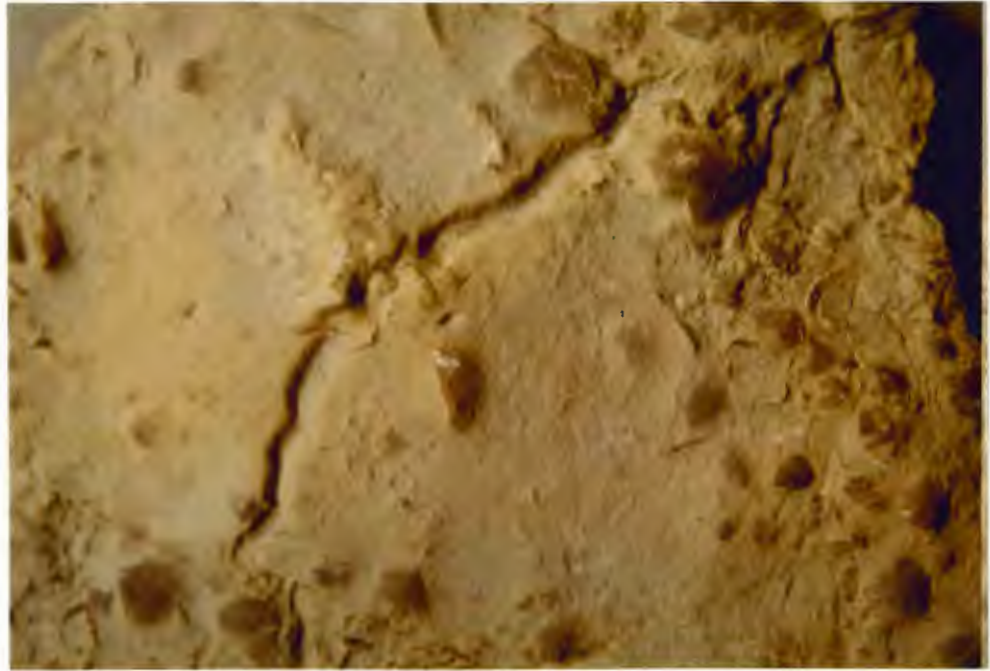


Figure A12 - Nereites sp.

Ichnogenus Palaeophycus Hall, 1847

Osgood 1970, pp.373 to 378; Hantzschel 1975, pp.W87 to W89, figure 54-4;
Pemberton and Frey 1982, pp.843 to 881, plate 1 figures 1-6,8-10, plate 2
figures 1-3,6, plate 3 figures 3-6, plate 4 figures 1-5.

Diagnosis: A subcylindrical to cylindrical, lined, infrequently branched, straight
to slightly sinuous, horizontal or at a low angle to bedding burrow
systems. Burrows are infilled with sediment of the same lithology and
texture as that of the host sediment.

Classification: Feeding burrow.

Remarks: Morphologically extremely similar to Planolites, but the latter's
burrows are filled with sediment of different lithology from the host
lithology. See presentations and discussions in Albert (1975) vs
Pemberton and Frey (1982).

Range: Precambrian to Recent.

Palaeophycus tubularis

Figure A13

Description: Per diagnosis, thin smooth unornamented walls, diameter 0.75 to
1.5 cm.

Remarks and occurrence: Relatively uncommon in the Platteville as are most
lined, walled burrows.

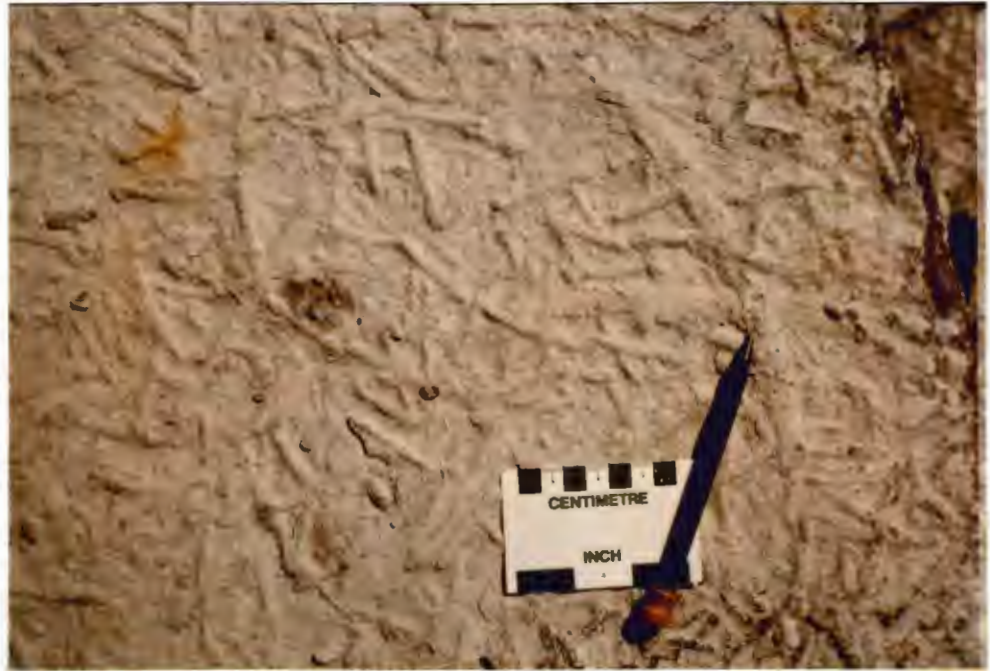


Figure A13 - Palaeophycus tubularis (the large burrows at the tip of the pencil) and Planolites bevererensis

Ichnogenus Planolites Nicholson, 1873

Pemberton and Frey 1982, pp.843 to 881, plate 2 figures 4,5,7-9 plate 3 figures 1,2,7-9 plate 5 figures 1,2; Hantzschel 1975, pp.W94 to 96, figures 59-5a,b.

Diagnosis: A subcylindrical to cylindrical, unlined, infrequently branched, straight to slightly sinuous, horizontal or at a low angle to bedding burrow systems. Burrows are infilled with sediment of a different lithology and texture as that of the host sediment.

Classification: Feeding burrow.

Remarks: Morphologically extremely similar to Palaeophycus, from which it is distinguished by the latter's burrows being filled with sediment of the same lithology as the host sediment. See presentations and discussions in Albert (1975) vs Pemberton and Frey (1982).

Range: Precambrian to Recent.

Planolites beverleyensis

Figure A13

Description: Per diagnosis, cylindrical unlined burrows range from 4.0 to 12.0 cm in length and in diameter from 0.5 to 1.0 cm, straight to slightly sinuous.

Remarks and occurrence: Second only to Chondrites as the most common type of burrow in the Platteville, found at all locations.

Planolites montanus

Figure A14

Description: A small curved cylindrical burrow up to 2.0 cm in length and less than 0.5 cm in diameter, unbranched.

Remarks and occurrence: Observed at Lucky Hill road cut in the Pecatonica Member and at the Saratoga road cut in the Carimona Member.



Figure A14 - Planolites montanus

Ichnogenus Rhizocorallium Zenker, 1836

Fursich 1974a, pp.16 to 28, plates 1-4; Hantzschel 1975, pp.W101 to 102, figure 63 1a,b; Pemberton and Frey 1984, pp.296 to 297, figure 11.

Diagnosis: A U-shaped burrow with spreiten orientated parallel or oblique to the bedding plane. Limbs are essentially parallel and usually have a ratio of tube diameter to spreite width of greater than 1:5.

Remarks: Believed to be of crustacean origin.

Classification: Feeding burrow.

Range: Cambrian to Tertiary.

Rhizocorallium sp.

Figure A15

Description: Per diagnosis, burrow diameter ranges from 1.0 to 2.0 cm.

Remarks and occurrence: The burrow was recognized only in slabbed limestone, and therefore the distribution is uncertain.



Figure A15 - Rhizocorallium sp.

Ichnogenus Rusophycus Hall, 1852

Osgood 1970, pp.301 to 308,412 to 415, plates 57 figures 1, 6, 58, 59 figures 1-6; Crimes 1975a, pp.37 to 41; Osgood and Drennan 1975, pp.299 to 349, plates 1-3; Hantzschel 1975, pp.W101 to 103, figures 63a 1a-1g; Bergstrom 1976, pp.1623 to 1629, figure 16.

Diagnosis: Bilobate coffee-bean like form possessing a large median furrow and anterolateral striae ranging from fine to coarse. Shape variable; width usually ranging from one-half to two-thirds the length.

Remarks: Classic member of Cruziana ichnofacies, formed by trilobites.

Classification: Resting trace.

Range: Precambrian to Permian.

Rusophycus sp.

Figure A16

Description: Per diagnosis, length ranges from 3.0 to 4.5 cm; width ranges from 1.2 to 1.8 cm. Two of the specimens are slightly curved and interconnect with another burrow a few cm away.

Remarks and occurrence: Relatively uncommon in the Platteville as are most epirelief traces. Specimens found at White Rock and Sogn road cuts, all from the upper Platteville-Decorah contact.

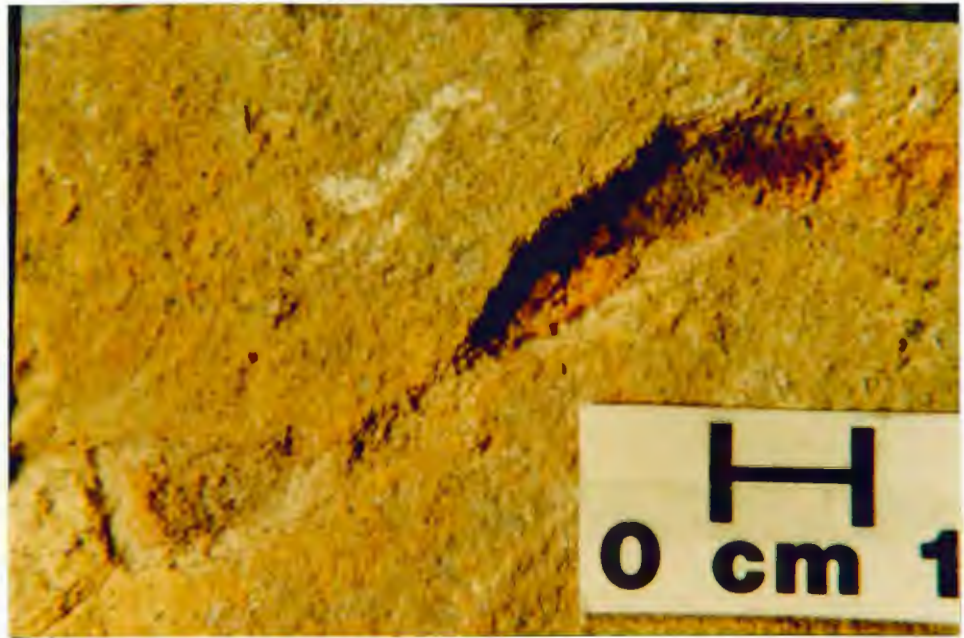


Figure A16 - Rusophycus sp.

Ichnogenus Skolithos Haldemann, 1840

Albert 1974, pp.661 to 668; Hantzschel 1975, pp.104,106,107, figure 64 2ab;

Sundberg 1983, pp.145 to 149, figure 2a-f.

Diagnosis: Cylindrical, unbranched, straight tubes perpendicular to bedding.

Diameters range from 1.0 to 15.0 mm, length may be up to 100 cm, more commonly around 30 cm. The burrows are commonly crowded together.

Remarks: Namesake of the Skolithos ichnofacies. Associated with shifting substrates and higher energy conditions.

Classification: Dwelling burrow.

Range: Precambrian to Tertiary.

Skolithos sp.

Figure 2

Description: Per diagnosis, diameters range from 0.5 to 1.3 cm, lengths reach 35 cm.

Remarks and occurrence: Observed in the St. Peter Formation, Nerstrand road cut.

Ichnogenus Subphyllochorda

Gotzinger & Becker, 1932

Hantzschel 1975, pp.W106 to 107, figures 66 2a-d; Ksiazkiewicz 1970, pp.289 to 291, plate 1 e-g.

Diagnosis: A ribbon-like trail consisting of a broad, medial stripe flanked by lateral sections with varied longitudinal markings. The trail may be extensive, up to 2 meters in length.

Classification: Crawling and feeding trace.

Remarks: Believed to be gastropod traces of wide facies range (Nereites and Cruziana).

Range: Cambrian to Tertiary.

Subphyllochorda sp.

Figure A17

Description: Very slightly convex (epirelief) 1.4 cm wide trail which has faint parallel striations (1.0 mm wide) one third of the way in from each side. A faint 1.0 mm wide lateral ridge on one side is present for a short distance. Smaller specimens have widths of approximately 2.0 mm and are less distinct.

Remarks and occurrence: Small specimens were obtained from the same bedding plane adjacent to the larger specimens at the White Rock and



Figure A17 - Subphyllochorda sp. the trail by the right lower corner of the card

Sogn road cuts. In all cases the specimens originated from rocks just below the Platteville-Decorah contact.

Ichnogenus Teichichnus Seilacher, 1955

Frey 1970, pp.17, plate 2 figure 2,4, plate 3 figure 7, plate 4 figures 1,6, plate 5 figures 2,4,7; Hantzschel 1975, pp.114 to 115, figure 63 4a,b; Archer 1984, p.292, figure 5e.

Diagnosis: Horizontal cylindrical burrow on top of U-shaped troughs which form spreiten. May be up to 50 cm long and 10 cm in height.

Remarks: May be very similar to a vertically oriented Rhizocorallium. Probably made by a number of different organism through time.

Classification: Feeding burrow.

Range: Cambrian to Recent.

Teichichnus sp.

Figure 20

Description: Per diagnosis, diameter of burrow ranges from approximately 0.4 to 1.0 cm. Heights up to 7 cm noted, length was not determinable.

Remarks and occurrence: Identified only in slabbed limestone blocks, the distribution is therefore uncertain. Problematica type I may be a member of this genus (?Teichichnus rectus).

Ichnogenus Thalassinoides Ehrenberg, 1944

Kern and Warme 1974, pp.893 to 899; Hantzschel 1975, pp.W113,115,117, figures 70 2a,b; Pemberton and Frey 1984, pp.299 to 301, figures 13 a-c; Kamola 1984, pp.533 to 536, figures 13-16.

Diagnosis: A 3-dimensional burrow system which consists of branching horizontal networks at multiple levels joined to each other and the surface by vertical shafts. Branching typically occurs as a Y or less frequently as a T, while swellings are common at branchings and other points. The diameter of the burrows is variable, but commonly ranges from 1.0 to 1.5 cm.

Classification: Dwelling (domichnia) and feeding burrow system.

Remarks: Thalassinoides has been noted to grade into the burrow Ophiomorpha from which it differs by having smooth walls.

Range: Ordovician to Recent.

Thalassinoides sp.

Figure 18

Description: Predominantly horizontal burrow network with a diameter of 0.75 to 2.5 cm sometimes swelling to 4.5 cm at turnarounds and branching points. Branches are most commonly a Y at 20 to 30 degree angle, less frequently as T branching at a angle of 70 to 90 degrees. The diameter of T branchings maybe considerable less than the main shaft.

Remarks and occurrence: Extremely prominent at several location, most notable at the Lucky Hill road cut.

Ichnogenus Torrowangea Webby, 1970

Webby 1970, pp.100 to 101, figures 18 a-d, 19; Hantzschel 1975, pp.W116 to 117, figure 72 4a-d.

Diagnosis: Consists of a sinuous to meandering trail with a diameter of 1.0 to 2.0 mm. Transverse annulation formed by irregular constrictions occur at intervals of 1.0 to 4.0 mm.

Classification: (?)Feeding trail.

Remarks: Webby was unable to determine if the trails were predepositional (at the sediment water interface) or postdepositional (below the sediment water interface).

Range: Late Precambrian to (?)Ordovician.

(?)Torrowangea sp.

Figure A9

Description: Consists of an irregular trail 1.0 to 3.0 mm in diameter broken into segments 1.0 to 5.0 mm in length (convex epirelief).

Remarks and occurrence: All samples obtained were from one location, the lowermost limestone bed within the Decorah Shale at White Rock road cut. Several segments have circular imprints of probable arthropod origin (Diplichnites) deforming them which would indicate they were

predepositional. If this is indeed Torrowangea, it would extend the genus's range from Precambrian to middle Ordovician.

Ichnogenus Trypanites Magdefrau, 1932

Bromley 1970, pp.63, figure 4b; Hantzschel 1975, pp.w124 & W136, figure 76;
Byers and Stasko 1978, pp.1304 to 1306, figure 2; Warne and McHuron 1978,
pp.67 to 118, figures 4,5,9,10; Ekdale et al 1984, p.121, figure 10-7.

Diagnosis: Excavations into hard or semi-consolidated substrates which
generally have abrupt wall boundaries and may cut through individual
grains.

Classification: Dwelling borings.

Remarks: The ichnogenus Trypanites was redefined by Bromley (1972) to
include a wide variety of borers including pouch-shaped types.

Range: Ordovician to Recent.

Trypanites weisei

Figures 21, 22

Description: A near vertical cylindrical boring 1.0 to 2.0 mm in diameter and up
to 2.5 cm in length

Remarks and occurrence: Common at numerous locations such as the east
Spring Grove but always restricted to the upper surface of a corrosion
zone or a bored object.

Trypanities sp. pouch-type

(?)Gastrocaenoites(?)

Figure 22

Description: Consists of a circular surface pit 0.7 cm in diameter connected to a vertical shaft 3.5 cms deep. At the lower end of the shaft an enlarged chamber descends at a 45 degree angle from the vertical. The chamber is 1.4 cm in height at maximum, and 2.0 cms long. The entire structure is filled with limonite which displays vertical scratches where the original full thickness remains. Smaller version pictured in figure 23 are 0.3 cm neck, 0.7 cm in depth, and 0.5 cm pouch diameter.

Remarks and occurrence: A specimen were obtained from float amid the Carimona Member of the Platteville at the Nerstrand road cut and the Rochester quarry.

Ichnogenus Problematica type I

Figure 19

Description: A horizontal straight burrow 0.4 to 0.5 cm in diameter and 4 to 5 cm in length. The ends turn abruptly up into the overlying carbonate bed and can sometimes be observed up to 4 cm into the sediment. X-rays indicate that the upturned tubes continue to separate slightly and have an spreiten between them.

Classification: Dwelling or feeding structure.

Remarks and occurrence: May be part of the genus Teichichnus, in which case it would probably be Teichichnus rectus. Found at numerous locations always in convex hyporelief.

Ichnogenus Problematica type II

Figure A9

Description: Consists of a single pair of slightly offset convex (epirelief) gentle tapering structures parallel to bedding, 3.0 to 5.0 cm long, 0.3 to 1.0 cm wide. The texture is markedly different from that of the surrounding sediments, having a far greater concentration of shell fragments and other particles possibly from packing after passage through the alimentary canal of an infaunal deposit feeder.

Classification: (?)Feeding burrow.

Remarks and occurrence: A single specimen was obtained from the contact between the Platteville and Decorah Formations, White Rock road cut. Numerous (?)Torrowangea, and Diplichnites occupy the same surface.

Ichnogenus Problematica type III

Figure A8

Description: Consists of gentle curving burrows or trails 0.5 mm in diameter and greater than 6.0 cm in length.

Classification: (?)

Remarks and occurrence: A single specimen was obtained at the contact between the Platteville and Decorah Formations, White Rock road cut.

Diplichnites sp. type I was found on the same sample.

APPENDIX II
USES AND CLASSIFICATION

Potential uses for Ichnology in Geology

- I. Paleontology
 - A. Fossil record of soft-bodied animals
 - B. Evidence of activity by organisms
 - C. Diversity of fossil assemblages
 - D. Evolution of the metazoa and of behavior
- II. Stratigraphy
 - A. Biostratigraphy of "unfossiliferous" rocks
 - B. Correlation by marker beds
 - C. Structural attitude of beds
 - D. Structural deformation of sediments
- III. Sedimentology
 - A. Production of sediment by boring organisms
 - B. Alteration of grains by sediment-ingesting animals
 - C. Sediment reworking
 - 1. Destruction of initial fabrics and sedimentary structures
 - 2. Creation of new fabrics and sedimentary structures
- IV. Depositional environments and paleoecology
 - A. Bathymetry
 - B. Temperature and salinity
 - C. Depositional history

1. Rates of deposition
 2. Amounts of sediment deposited or eroded
- D. Aeration of water and sediments
 - E. Substrate coherence and stability
- V. Consolidation of sediments
- A. Initial history of lithification
 - B. Measures of compaction
-

From Frey and Seilacher (1980).

Ethological Classification of Bioturbation Structures

Resting traces (Cubichnia):

Shallow depressions made by animals that temporarily settle onto, or dig into, the substrate surface. Emphasis is upon reclusion.

Crawling traces (Repichnia):

Trackways, surficial trails, and shallow horizontal structures made by organisms traveling from one place to another. Emphasis is upon locomotion.

Grazing traces (Pascichnia):

Grooves, pits, and furrows, many of them discontinuous, made by mobile deposit feeders at or near the substrate surface. Emphasis is upon feeding behavior analogous to "strip mining."

Feeding structures (Fodicichnia):

More or less temporary burrows structures constructed by deposit feeders, the structures may also provide shelter for the organisms. Emphasis is upon feeding behavior analogous to "under-ground mining."

Dwelling structures (Domichnia):

Burrows or dwelling tubes providing more or less permanent domiciles, mostly for hemisessile suspension feeders or, in some cases, carnivores.

Emphasis is upon habitation.

Escape structures (Flecichnia):

Trace fossils of various kinds modified or made anew by animals in direct response to substrate degradation or aggradation. Emphasis is upon readjustment, or equilibrium between relative substrate position and the configuration of the contained traces.

Adapted from Seilacher (1953), Frey (1971), and Simpson (1975), in Frey (1978).

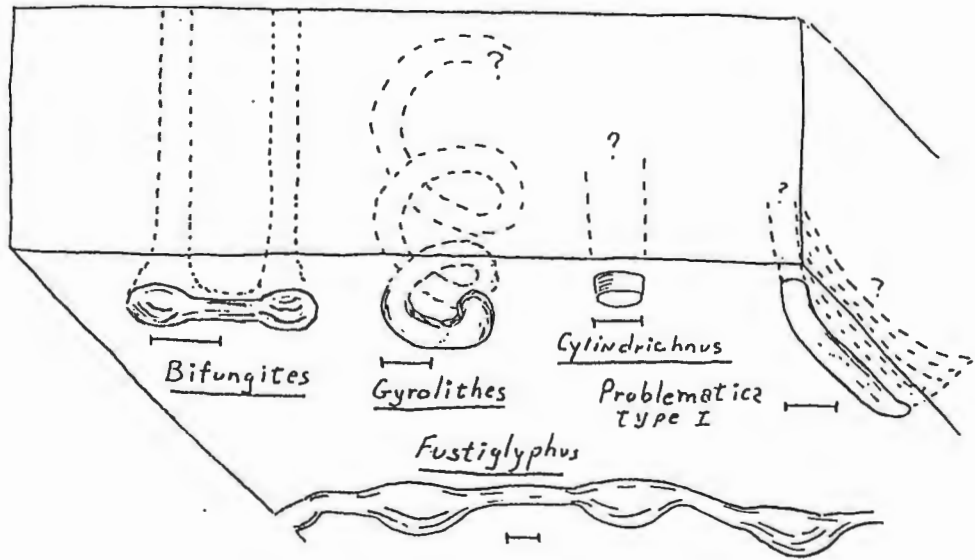
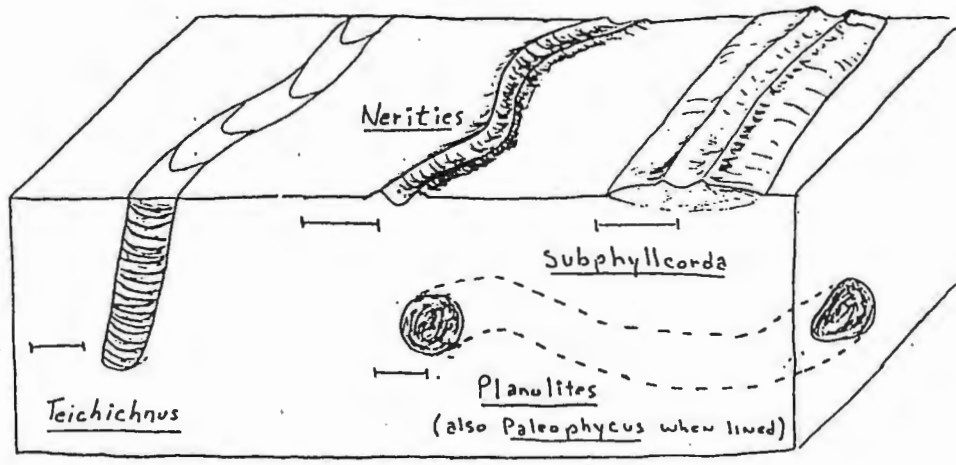
APPENDIX III
OUTCROP LOCATIONS

Outcrop Locations

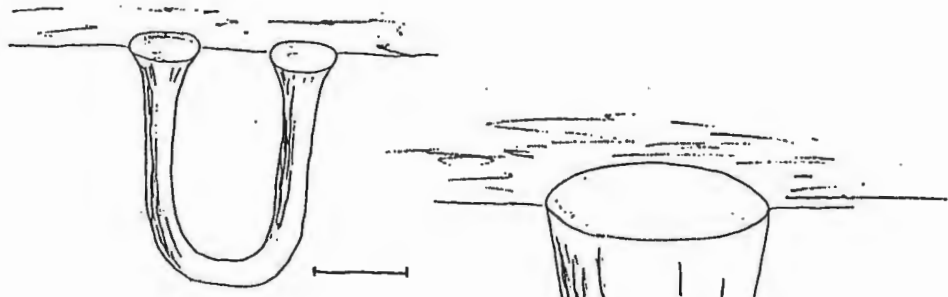
- 1 - South Spring Grove Quarry: Houston County, SW1/4, SE1/4 Section 36, T101N, R7W
- 2 - East Spring Grove Quarry: Houston County, SE1/4, SE1/4, NE1/4, Section 5, T101N, R6W
- 3 - West Spring Grove Quarry: Houston County, NW1/4, NE1/4, NE1/4, Section 20, T101N, R7W
- 4 - North Mabel Quarry: Fillmore County, SW1/4, SE1/4, & SE1/4, SE1/4, Section 15, T101N, R8W
- 5 - Preston Road Cut: Fillmore County, North side of Hwy 52, Central Section 4, T102N, R10W
- 6 - South Fountain Road Cut: Fillmore County, East side of Hwy 52, W1/2, SW1/4, Section 14, T103N, R11W
- 7 - Cummingsville Road Cut: Olmsted County, SE1/4, NW1/4, Section 28, T105N, R12W
- 8 - Chatfield Road Cut: Fillmore County, NE1/4, NW1/4, Section 5, T104N, R11W
- 9 - East Chatfield Quarry: Olmsted County, SW1/4, SW1/4, Section 33, T104N, R11W
- 10 - Lucky Hill Road Cut: Olmsted County, SE1/4, NE1/4 Section 35, T105N, R10W
- 11 - South Saratoga Road Cut: Winona County, North edge of SE1/4, Section 18, T105N, R10W
- 12 - North Saratoga Quarry: Winona County, SE1/4 Section 31, T106N, R10W
- 13 - South St. Charles Road Cut: Olmsted County, SE1/4, Section 22, T106N, R11W
- 14 - North Viola Quarry: Olmsted County, North side of Hwy 9, 1 1/2 mile east of intersection with county 7, South edge of SE1/4, Section 3, T107N, R12W

- 15 - Golden Hill Road Cut: Olmsted County, West side Hwy 52, NW1/4, Section 14, T106N, R14W
- 16 - Daneville Quarry: Olmsted County, S1/2, NE1/4, Section 18, T107N, R15W
- 17 - North Douglas Quarry: Olmsted County, S1/2, NW1/4, SE1/4, Section 26, T108N, R15W
- 18 - North Pine Island Quarry: Goodhue County, SW1/4, NW1/4, Section 18, T109N, R15W
- 19 - Wanamingo Quarry: Goodhue County, SW1/4, NW1/4, SE1/4, Section 29, T110N, R16W
- 20 - Faribault Quarry: Rice County, SW1/4, SW1/4, Section 33, T110N, R20W
- 21 - Nerstrand Quarry and Road Cut: Rice County, N1/2, SE1/4, Section 9, T110N, R19W; SE1/4, SW1/4, Section 3 & NE1/4, NW1/2, Section 10, T110N, R19W; SW1/4, SW1/4, Section 35, T111N, R19W
- 22 - Cannon Falls Quarry and Road Cut: Goodhue County, S1/2, SE1/4, Section 18, T112N, R17W; SE1/4, SW1/4, Section 20, T112N, R17W
- 23 - White Rock Quarry and Road Cut: Goodhue County, NW1/4, Section 4, T112N, R16W; SE1/4, SE1/4, Section 31, R16W, R112N
- 24 - Wangs Quarry: Goodhue County, SE1/4, NE1/4, Section 5, T111N, R18W
- 25 - South Sogn Road Cut: Goodhue County, NW1/4, SE1/4, Section 24, T111N, R18W; Center of Section 36, T111N, R18W; E1/2, NW1/4 & SW1/4, Section 1, T111N, R18W
- 26 - South Shadow Falls Park: Ramsey County, SW1/4, NE1/4, Section 5, T28N, R23W
- 27 - Hidden Falls Park: Ramsey County, SE1/4, Section 17, T28N, R23W
- 28 - Airport Road Cut: Hennepin County, freeway roadcuts around Section 29, T28N, R23W

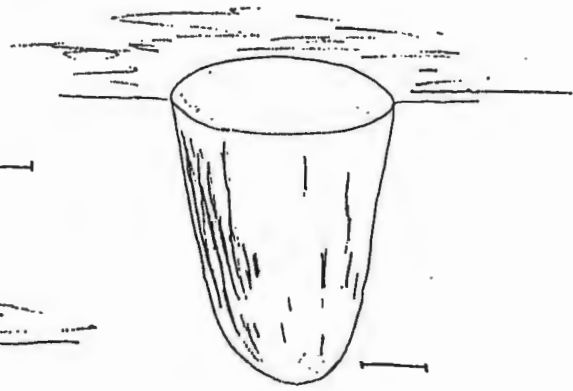
APPENDIX IV
TRACE FOSSIL SKETCHES



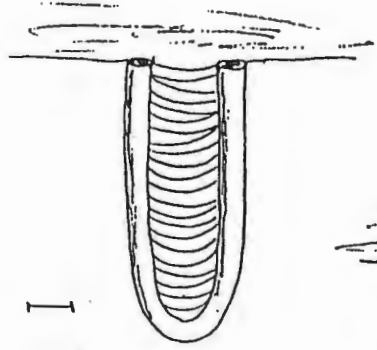
Sketches from field and laboratory notebooks. Bar scale(s) = 1 cm



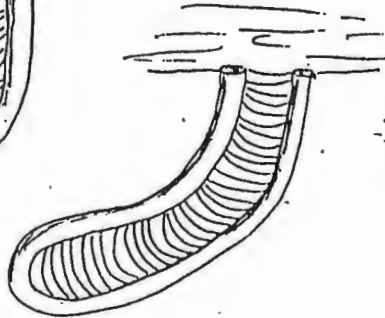
Arenicolites



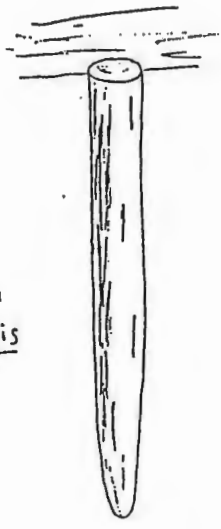
Canostichus



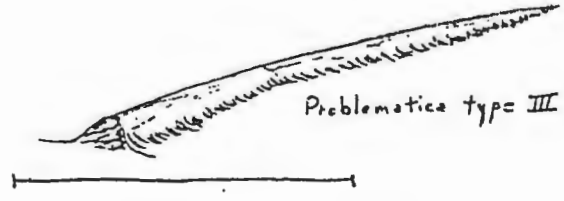
Diplocsterion



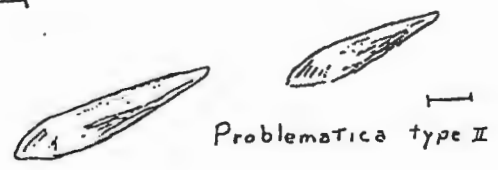
Rhizocorallium



Skolithis



Problematice type III



Problematice type II



(?) Torrowangea

